REPORT TO THE LEGISLATURE

FEBRUARY 2025

Reuse and recycling of solar installations at end of life

Recommendations for a statewide management system

MINNESOTA POLLUTION CONTROL AGENCY

Reuse and recycling of solar installations at the end of life

Report to the Legislature, February 2025

About this report

The Minnesota Pollution Control Agency (MPCA) engaged Management Analysis and Development (MAD) to facilitate the Solar Installation Recycling and Reuse Policy Working Group and to draft this report on behalf of MPCA. MAD is Minnesota government's in-house fee-for-service management consulting group, offering quality consultation services to local, regional, state, and federal government agencies and public institutions.

Legislative Charge

Minnesota Statute: 2023 Session Laws, Chapter 60, Art. 1, Sec. 2, Subd. 7(m); Art. 3, Sec. 36.
The commissioner of the Pollution Control Agency, in consultation with the commissioners of commerce and employment and economic development, must coordinate preparation of a report on developing a statewide system to reuse and recycle solar photovoltaic modules and installation components in the state.

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Policy Working Group members

Members of the policy working group are listed in Appendix A.

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Alternative formats

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Executive summary

The expansion of solar energy in Minnesota and worldwide is driving the need for responsible management of solar photovoltaic modules and installation components (solar installations) at their end-of-life (EOL). Without action, Minnesota faces significant environmental, economic, and logistical challenges as solar waste is expected to grow exponentially in the coming decades. The 2023 Minnesota Session Law (Laws of Minnesota 2023, chapter 60, article 3, section 36) mandates a study and recommendations for a comprehensive, statewide system for EOL solar installations, offering Minnesota a pivotal opportunity to act now and shape a sustainable future.

The case for action

Solar energy is critical to Minnesota's clean energy transition, but with increasing solar installations comes a growing waste stream (Minnesota Pollution Control Agency, *Minnesota Climate Action Framework)*. According to projections from Eunomia Research and Consulting (Eunomia), the group contracted by MPCA to conduct a comprehensive study supporting the development of the Policy Working Group (PWG) recommendations, solar installation waste will peak in Minnesota by 2040, driven by the early retirement of panels, storm damage, and the shorter lifespan of associated components like inverters. If no new policies are enacted, only 30 percent of this waste will be recycled, with the majority ending up in landfills. This would result in lost economic opportunities, environmental degradation, and a strain on waste management infrastructure.

By establishing a recycling and reuse system now, Minnesota can avoid these outcomes, create jobs, and recover valuable materials such as aluminum, silver, and silicon. These materials are critical to the clean energy supply chain and represent significant economic value. For example, the solar industry is projected to demand 20 percent of global silver supply by 2027, underscoring the need for effective recycling (Stock 2024).

Recommendations for action

The MPCA recommends a statewide disposal ban and recycling requirements, drawing heavily from the PWG's work and Eunomia's scenario modeling. These recommendations prioritize long-term environmental and economic sustainability while addressing the unique needs of Minnesota's communities.

- **Disposal ban for all solar installations**: Prohibits landfilling, incineration, and improper disposal of solar installations, ensuring that all EOL materials are either reused (encouraged) or recycled (mandatory). This policy would include a system aimed at minimizing waste and maximizing the continual use of resources by reusing, recycling, and recovering materials for new production and consumption, to keep valuable materials in the circular economy.
- **Statewide recycling requirements for all solar installations**: Requires recycling for all solar installations, regardless of size, to maximize material recovery and reduce waste, ensuring alignment with state sustainability goals.
- **Lowering decommissioning requirements:** Reduces the current 50 Megawatts Direct Current (MW DC) threshold for mandatory decommissioning and recycling requirements to installations larger than 1 MW DC, including all co-located Community Solar Gardens (CSGs). This creates a market for end-of-life

management for larger installations, incentivizing compliance, fostering innovation in recycling technologies, and ensuring these systems contribute to sustainable material recovery.
- **Creation of a Central Management Organization (CMO):** Establishes a centralized entity to provide logistical and operational support for all installations 1 MW DC and below, ensuring cost effective compliance for smaller installations through streamlined collection, transportation, and recycling processes.

Benefits of acting now

According to the systems options report by Eunomia, implementing these policies would require investment but would offer substantial long-term benefits. The benefits would include:

- **Environmental gains**: Diverting 76-94 percent of solar waste from landfills, reducing environmental impacts, and mitigating greenhouse gas emissions from material extraction and production phases.
- **Economic opportunities**: Creating jobs across the recycling value chain and establishing Minnesota as a leader in solar recycling infrastructure.
- **Supply chain benefits**: Recovering high-value materials like silver, copper, and aluminum, which would provide cost savings and enhance supply chain resilience and reduce dependency on volatile global markets for critical resources.
- **Community benefits**: Ensuring underserved and Tribal communities have equitable access to sustainable waste management solutions.

Failing to act now would risk leaving Minnesota with an unmanageable solar waste problem by mid-century, along with missed economic and environmental opportunities.

Conclusion: A critical moment for Minnesota

The MPCA's recommendations reflect an important consensus among stakeholders, including representatives from the solar industry, government entities, Tribal Nations, and environmental organizations. By adopting these measures, Minnesota would establish itself as a national leader in solar waste management, aligning with the state's sustainability goals and creating a robust, equitable, and economically beneficial system.

The time to act is now. Implementing these policies would not only address an imminent waste challenge but also position Minnesota to reap the benefits of a sustainable, circular economy.

Introduction

Legislative charge

The 2023 Minnesota Session Law (Laws of Minnesota 2023, chapter 60, article 3, section 36) requires a comprehensive study and reporting process to establish a statewide system for the end-of-life (EOL) management of solar photovoltaic modules and installation components (hereafter referred to as solar installations, which consist of solar photovoltaic modules and installation components). This directive required the Minnesota Pollution Control Agency (MPCA), in collaboration with the Department of Commerce (Commerce) and the Department of Employment and Economic Development (DEED), to develop a report with system options (hereafter referred to as the system options report) that address the collection, reuse, and recycling of solar installations.

The law required that the proposed system:

- Be convenient and accessible throughout the state
- Recover 100 percent of discarded components
- Maximize value and materials recovery from solar installations

Required analysis for system options

The law specified that any system options proposed include a detailed analysis of:

1. The reuse and recycling values of solar installations and recovered materials
2. System infrastructure and technology needs
3. How to maximize in-state employment and economic development
4. Net costs for the program
5. Potential benefits and negative impacts of the plan on environmental justice and Tribal communities

Survey and future projections

The legislation required that the system options report include a comprehensive survey of solar installations currently being decommissioned, along with projections for future EOL materials in Minnesota. Additionally, it was required to analyze current EOL management practices and project how these materials would likely be managed in the future if the proposed system were not implemented. These projections are intended to guide policy decisions and to promote a robust and forward-looking system. All of this information can be found in the 'Solar PV Panel Reuse and Recycling Study' by Eunomia Consulting, included as Appendix E.

Policy working group

Following the completion of the systems options report, MPCA was instructed to convene a working group to advise on the development of policy recommendations for the statewide management of solar installations. This Policy Working Group (PWG) was required to include, but was not limited to:

- The commissioners of Commerce and DEED or their designees
- Representatives from the solar industry and electric utilities
- Representatives from state, local, and Tribal governments
- Other relevant stakeholders

The MPCA is required to submit the systems options report and MPCA's recommendations to the relevant legislative committees.

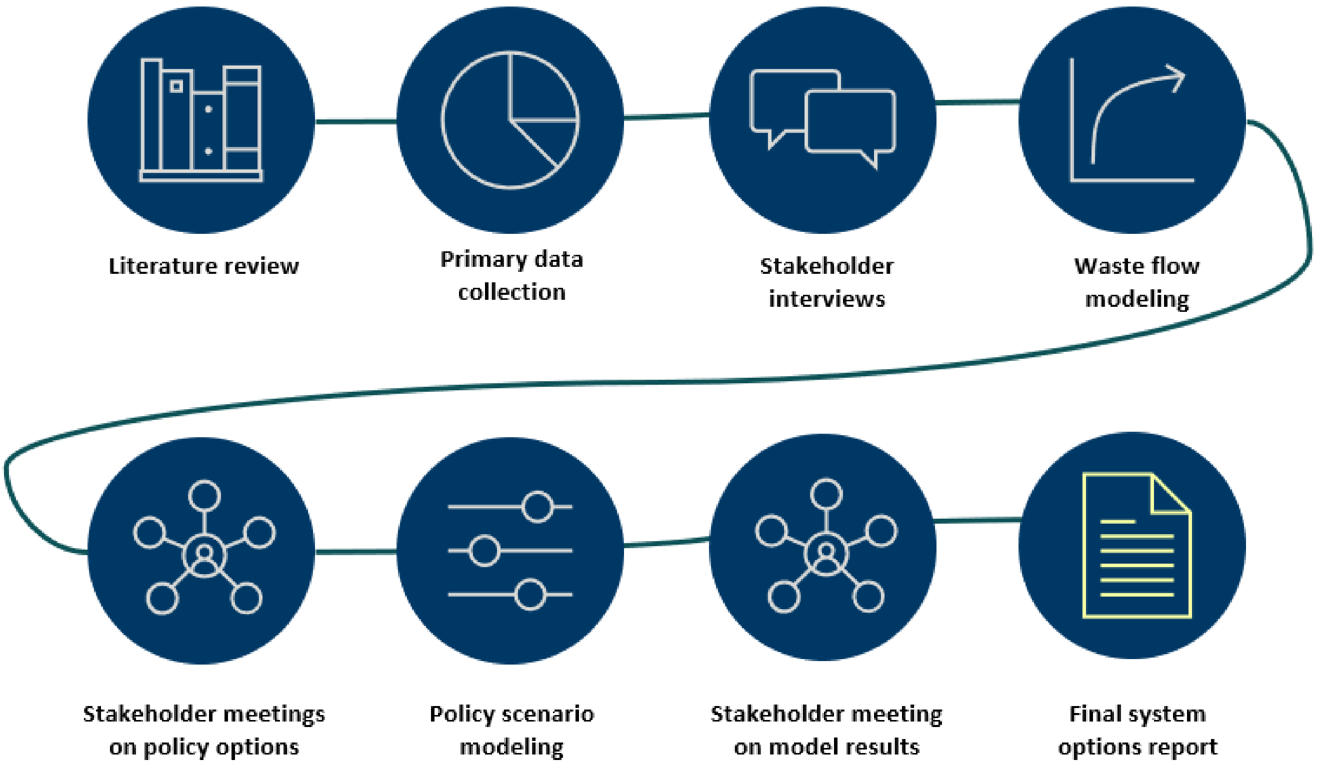
Systems options report by Eunomia

To fulfill the legislative requirements, MPCA contracted with the research group Eunomia, in collaboration with the Product Stewardship Institute (PSI), to conduct a comprehensive study to support development of a systems options report. An overview of Eunomia's project approach is shown in Figure 1, and detailed activities are outlined below for further context:

- Eunomia began with an in-depth literature review of the regulatory landscape for solar installation EOL management in the United States and internationally. This review provided critical insights into existing policies and best practices, forming the basis for the suite of policies recommended for analysis in the study.
- The project team gathered and analyzed extensive data on solar installation waste, economic factors, and programmatic considerations across residential, commercial, and utility-scale installations. This data supported a comprehensive understanding of Minnesota's current solar installation waste landscape and future challenges.
- Eunomia conducted one-on-one interviews and workshops with stakeholders involved in the process of solar installation, from start to finish, to refine policy options and gather input on potential system requirements. These engagements helped shape the modeling assumptions and provided input for designing policy scenarios.
- Eunomia's modeling approach included waste flow and scenario modeling exercises, which estimated current and projected solar installation waste generation for various policy scenarios. Five distinct scenarios (plus a baseline, no-new-policy scenario) were modeled, examining variables such as deinstallation, collection, consolidation, transportation, dismantling, and program management costs, and their impact on program performance to meet the legislated objectives noted above.
- The project team presented model results to the PWG for feedback, allowing for an iterative refinement process.

Eunomia's study findings are the basis of the PWG's policy recommendations. The system options report, 'Solar PV Panel Reuse and Recycling Study' by Eunomia Consulting, is included as Appendix E.

Figure 1. Eunomia's project approach (figure designed by Eunomia)



Policy Working Group overview

In February 2024, MPCA, with support from Management Analysis and Development (MAD), and in collaboration with Commerce and DEED, launched the PWG. The PWG brought together representatives from various sectors, including the solar and electrical industries, state and local governments, Tribal governments, and other stakeholders. A complete list of PWG participants is included in Appendix A: Policy Working Group Members.

PWG meeting timeline and key topics

MAD began by holding individual orientation sessions with PWG members in June and July 2024, before the first official PWG meeting on August 1, 2024. The PWG then met regularly through November 2024 to discuss and refine their policy recommendations:

- Meeting #1 (August 1): Welcome and setting the stage
- Meeting #2 (August 27): Background and history of solar installation EOL management
- Meeting #3 (September 5): Defining success for the PWG
- Meeting #4 (September 19): Presentation by Eunomia on draft findings and feedback
- Meeting #5 (October 3): Initial policy recommendations
- Meeting #6 (October 17): Further development of recommendations
- Meeting #7 (October 30): Finalizing recommendations
- Meeting #8 (November 19): Confirmation of the final recommendations

The PWG presented their recommendations to the Commissioner in December 2024.

PWG recommendations

The PWG made four main recommendations to the Commissioner which can be seen in Appendix C and include:

- Mixed Municipal Solid Waste (MMSW) disposal ban for all solar installations
- Statewide recycling requirements for all solar installations, with goal of high level (comprehensive) recycling after five years to maximize material and value recovery
- Decommissioning requirements for installations above 1 MW DC and co-located CSGs
  - Permittee (owner) pays for recycling of installations above 1 MW DC
- Creation of a Central Management Organization (CMO) for installations 1 MW DC and below
  - CMO provides financial and/or technical assistance to permittees/owners of smaller installations to ensure they have the resources for proper recycling

Key terms

This section provides definitions and explanations of key terms used throughout this report, in order to promote consistent understanding of the scope, processes, and standards related to EOL management of solar installations. These definitions were created by the PWG and by MAD in collaboration with MPCA.

Defining solar installations

For MPCA's recommendations, solar installations are defined as a combination of solar photovoltaic modules and installation components:

- **Solar photovoltaic modules (solar panels)**: Solar panels designed for energy generation
- **Installation components**: Material used to install and hold solar panels in place or collect energy from panels, such as bracketing, wiring, inverters, and batteries

Defining scale of installations

Solar installations are referenced in a variety of scales throughout this report including:

- **Residential installations:** Solar installations on homes
- **Commercial and industrial installations**: Solar installations used by businesses or in industrial applications
- **Utility-scale installations**: Large-scale solar installations supplying power to the grid
- **Community Solar Gardens (CSGs):** Shared solar installations serving multiple subscribers. Some CSGs may be co-located, meaning multiple gardens are situated at the same site, which can collectively result in a larger combined installation
- **Small-scale systems used for dedicated energy applications:** Solar installations used for off-grid or backup power, such as those installed in sheds or cabins

The MPCA's recommendations do not include consumer-grade solar products and other small electronics with embedded solar components, such as solar-powered garden lights, calculators, or emergency radios. These items are categorized as electronic waste. The MPCA's recommendations are focused on larger energy-generating solar systems that are not consumer electronics.

Defining material recovery

For clarity and consistency in the recommendations, these terms related to recycling and material recovery are defined:

- **Collection:** The process by which manufacturers, distributors, retailers, or other responsible parties accept solar installations from permittees or users for proper EOL management. Collection programs may include collection, transportation, and coordination of reuse, recycling, or disposal activities.
- **Recycling:** The process of converting solar installations into reusable materials by recovering valuable materials while safely managing hazardous elements. Recycling differs significantly between solar panels and installation components:
  - **Solar panels:** Recycling solar panels involves intricate processes to extract valuable materials like silicon, rare metals, and glass from complex, layered designs. These processes require advanced technologies and specialized facilities.
  - **Installation components:** Components such as inverters, racking, and supports are typically made of readily recyclable materials, like metals that can be processed through existing recycling channels.
- **Material Recovery:** The extraction of valuable materials or resources from solar installations at EOL. Recovery may include recycling as well as other processes, such as material repurposing, where components or raw materials are salvaged and used in new applications, contributing to resource efficiency and waste minimization. Material recovery from recycling is typically categorized as either 'high level' or 'limited:' note that the overall material recycling rate may not vary significantly based on the recycling 'level' since the weight percent recovery may differ by only about 10 percent. However, that 10 percent contains most of the panel material value in metals and semiconductor materials. The additional cost of high-level recycling is largely recovered through this material value.
  - **High Level or Comprehensive (term used by Eunomia):** Processes that recover glass, aluminum, valuable metals, and semiconductor materials at mass recovery rates exceeding 90 percent and in accordance with third party standards including but not limited to the European Committee for Electrotechnical Standardization (CENELEC) EN50625-2-4 and TS50625-3-5, Sustainable Electronics Recycling International (SERI) R2V3, or comparable United States or international standards.
  - **Limited:** Processes that recover glass and aluminum frames at mass recovery rates that typically do not exceed 80 percent, and do not recover other metals or semiconductor materials.
- **Circular economy:** a system aimed at minimizing waste and maximizing the continual use of resources by reusing, recycling, and recovering materials for new production and consumption.

Measurement standards

Throughout this report solar installation capacities are measured in megawatts of direct current (MW DC) to maintain consistency and accuracy. This aligns with industry standards and provides a consistent measurement for all size-related requirements, recommendations, and thresholds.

MPCA's recommendations

The MPCA heavily utilizes the PWGs recommendations, which reflect a balanced and comprehensive approach to managing EOL solar installations in Minnesota. These recommendations, informed by the Eunomia systems options report and robust stakeholder input, align with legislative requirements to recover 100 percent of discarded components, maximize material recovery, and promote environmental sustainability.

The MPCA's recommendations establish a statewide system for EOL solar management through a disposal ban and recycling requirements for all solar installations, regardless of size:

- **Disposal ban for all solar installations**: Prohibits landfilling, incineration, and improper disposal of solar installations, ensuring that all EOL materials are either reused (encouraged) or recycled (mandatory). This would keep valuable materials in the circular economy.
- **Statewide reuse and recycling requirements for all existing and new solar installations**: All installations, regardless of size, would need to be recycled, using high value recycling practices within a five-year time frame to maximize material and value recovery. Larger installations would use existing decommissioning standards, while smaller installations would receive support from a newly established Central Management Organization (CMO) to ensure cost-effective compliance (see two approaches below):
  - **Approach A:** Decommissioning requirements for installations above 1 MW DC and co-located CSGs
    - Funded by permittees
    - Requires reuse or recycling
    - Lowers current decommissioning process from 50 MW DC to above 1 MW DC
    - Includes all co-located CSGs
    - Includes existing and new installations
    - Harmonizes decommissioning standards across jurisdictions
    - Disposal ban and recycling requirement implemented now [existing recycling facilities are sufficient to manage until new decommissioning framework is established]
  - **Approach B:** Creation of a Central Management Organization (CMO) for installations 1 MW DC and below
    - Could be funded by one or multiple options: permittees, producers, wholesalers, rate payers, utilities
    - Requires reuse or recycling
    - Includes existing and new installations
    - CMO provides logistical and operational support to help small installations comply with recycling requirements
    - CMO implemented within 12-24 months
    - Disposal ban and recycling requirement implemented now [existing recycling facilities are sufficient to manage until the CMO is established]

The MPCA heavily utilizes the PWG's solar installation recycling recommendations. These recommendations offer a practical and equitable framework. The following shares more details on how to implement these recommendations to ensure effective, statewide EOL management for solar installations.

Recommendation: Disposal prohibition

To address improper disposal and promote a circular economy, the MPCA recommends an immediate and comprehensive prohibition on the landfilling, incineration[1], and improper disposal of solar installations, regardless of their size or lifecycle stage. All EOL materials must either be reused (encouraged) or recycled (required).

[1] This would not include thermal processing for metals recovery.

Implementation timeline

The MPCA recommends that the disposal ban take effect now. There are sufficient recycling facilities to manage discarded solar installation materials while the new decommissioning and CMO frameworks are implemented.

No exemptions policy

The MPCA supports a “no exemptions” policy to ensure full compliance and prevent exploitation. In rare cases where solar installations are deemed non-recyclable due to condition or technology, MPCA will manage exemptions on a case-by-case basis.

Discourage out-of-state disposal

To oversee compliance, MPCA recommends the following measures:

- Implement mechanisms to discourage out-of-state disposal, including:
    - Tracking the weight and destination of materials sent for recycling, such as reporting requirements for collectors on weight sent for recycling and recyclers on weight received and recycled.
    - Requiring certifications of recycling as part of decommissioning plans.
    - Ensuring small-scale installations managed through the CMO have no EOL costs, reducing the risk of stockpiling or illegal disposal.

Recommendation: Statewide reuse and recycling requirements

The MPCA recommends implementing statewide reuse and recycling requirements and aid its implementation through the lowering the size threshold for mandatory decommissioning plans for larger installations and the creation of a Central Management Organization:

- **Collection, reuse, and recycling goals:**
    - Collection of 100 percent of discarded solar installations for the purpose of reuse and recycling.
    - Establish a framework to support reuse, including rapid testing protocols to assess electrical and structural integrity, standards for reuse, third party certification to applicable standards, a warranty for market confidence in the product, and standardized pricing that reflects the income potential of the product when reused.
    - For recycling, at least 90 percent material recovery (by weight) in line with the European Committee for Electrotechnical Standardization (CENELEC) EN50625-2-4 and TS50625-3-5, Sustainable Electronics Recycling International (SERI) R2V3 or comparable United States or international standards. This goal should prioritize the recovery of valuable metals and materials, including silicon and other semiconductor materials, as well as high-quality glass, to advance a circular economy and sustainable material management.

Approach A: Decommissioning plan requirements

New threshold: Change the current 50 MW DC decommissioning threshold to greater than 1 MW DC and all co-located Community Solar Gardens (CSGs).

Permittees would be required to:

- Plan for the reuse (encouraged) or recycling (required) of all EOL solar installations.
- Provide updated cost estimates and financial assurances to ensure compliance with EOL management requirements.
- Submit plan updates every five years to incorporate evolving technologies and best practices.
- Obtain certificates of recycling to confirm compliance and proper management.

Working group development: For existing and new installations between 1 and 50 MW DC as well as co-located CSGs, the MPCA will convene a working group including PUC, Commerce, LGUs, representatives of the solar industry, and other relevant stakeholders, to harmonize decommissioning requirements, creating a unified regulatory approach statewide.

Approach B: Creation of a Central Management Organization (CMO).

To address the unique needs of smaller installations (1 MW DC and below), a CMO should be established to provide logistical and financial solutions for cost-effective EOL management.

Key responsibilities of the CMO:

- Prepaid collection, transportation, and recycling services for small installations.
  - No EOL fees for the permittee/owner.
  - CMO operations can be funded through multiple options. See possible funding mechanisms below.
- Certificates of recycling to confirm compliance and proper management. These would be provided by the recyclers to the CMO.
- Providing services to small installations with no fees at EOL will minimize illegal disposal and stockpiling.

Funding mechanisms: The CMO's operations could be funded through one or more sources, including permittees, producers, wholesalers, ratepayers, and utilities. Adjustments to funding tools, such as the Value of Solar Tariff (VOST) and net metering rates, could be made to ensure sustainable financing throughout a solar installation's lifecycle.

Implementation timeline: The MPCA recommends the CMO become operational within 24 months of policy approval. Immediate implementation of the disposal ban and statewide recycling requirements for installations under 1 MW DC will provide incentives for expedited implementation of the CMO.

Working group development: To establish the CMO effectively, the MPCA will create a working group to recommend the organization's governance structure, oversight, funding, and reporting requirements. This group will include representatives from relevant stakeholder organizations.

Financial incentives to support implementation

To accelerate the development of recycling infrastructure and ensure equitable implementation, the MPCA recommends targeted financial incentives, including grants, subsidies, and tax credits. These incentives will:

- Promote investment in Minnesota-based recycling infrastructure.
- Support job training programs for solar recycling technologies through DEED or Minnesota State Colleges and Universities (MNSCU).
- Encourage the development of testing and certification procedures and standards for reuse and innovative recycling technologies for high value and critical material recovery**.**

Conclusion

Implementing the MPCA recommendations would be an important step toward establishing a responsible, statewide system for managing EOL solar installations in Minnesota. These MPCA policy recommendations are drawn from a majority viewpoint communicated by PWG members, which included a diverse array of stakeholders—representatives from the solar industry, state and local governments, Tribal communities, environmental advocates, and recycling experts. The recommendations not only address the pressing environmental need for responsible solar installation disposal but also aim to streamline logistics, support economic development, and promote material recovery, aligning with the goals of the 2023 Minnesota Session Law.

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SOREN. Missions and Values.

Appendix A: Policy Working Group Members

Organization Name	Working Group Members	Organization Background
BlueGreen Alliance	Abby Hornberger	BlueGreen Alliance | About Us
Clean Energy Economy Minnesota	George Damian Gregg Mast	About Clean Energy Minnesota
Conservation Minnesota	Nels Paulsen James Lehner	Home | Conservation MN
Cosmic Recycling	Donnie Hopp	Cosmic Recycling
CURE MN	Hudson Kingston Maggie Schuppert	About Us | CURE
Department of Commerce	Jack Kluempke Suzanne Steinhauer Raymond Kirsch	About Us / Minnesota.gov
Department of Employment and Economic Development (DEED)	Ed Hodder	About Us / Minnesota Department of Employment and Economic Development
Dynamic Lifecycle Innovations	Casey Hines Haley Stauffacher	Dynamic Lifecycle Innovations' Leadership In ITAD & E-Recycling
EDF Renewables	Adam Sokolski Emma Wheal	About EDF Renewables Project Development | Wind Asset Management
First Solar	Pascal Caputo Karen Drozdiak	Overview | First Solar
Fresh Energy	Justin Fay	About Us - Fresh Energy
Great Plains Institute	Brian Ross	Who We Are | Great Plains Institute
Heliene	Martin Pochtaruk	About Us - HELIENE
Integrated Recycling Technologies (IRT)	Steve Budd Tony Celt	Learn More About Integrated Recycling Technologies | IRT
Midwest Renewable Energy Association (MREA)	Nick Hylla	About - Midwest Renewable Energy Association
Minnesota Association of County Planning & Zoning Administrators (MACPZA)	Marc Telecky	About MACPZA
Minnesota Association of Townships	Jane Youngkrantz	About Minnesota Association of Townships
Minnesota Power	Paul Helstrom	About Us - Minnesota Power is an ALLETE Company
Minnesota Solar Energy Industries Association (MnSEIA)	Logan O'Grady Curtis Zaun David Moberg Sarah Whebbe	Mission & History | MnSEIA
Public Utilities Commission (PUC)	Bret Eknes Jacques Harvieux	About Us / Public Utilities Commission

Organization Name	Working Group Members	Organization Background
Solar Energy Industries Association (SEIA)	Evelyn Butler Robert Nicholson	Our Work – SEIA
SolarCycle	Nick Cain	About SOLARCYCLE
Tribal government representatives	Brandy Toft Andrew Boyd Charlie Lippert Andrea Zimmerman Eugene Strowbridge	
Xcel Energy	Roger Clarke Luke Kusilek	About Us | Corporate | Xcel Energy

Appendix B: Abbreviations and acronyms

- Cathode-ray tube (CRT)
- Central management organization (CMO)
- Community solar gardens (CSG)
- Department of Commerce (Commerce)
- Department of Employment and Economic Development (DEED)
- End-of-life (EOL)
- Local government unit (LGU)
- Management Analysis and Development (MAD)
- Megawatts of direct current (MW DC)
- Minnesota Pollution Control Agency (MPCA)
- Minnesota Solar Energy Industries Association (MnSEIA)
- Mixed Municipal Solid Waste (MMSW)
- Photovoltaic (PV)
- Policy Working Group (PWG)
- Solar photovoltaic modules (solar panels)
- Solar Energy Technologies Office (SETO)
- Universal Waste (UW)
- The Value of Solar Tariff (VOST)

Appendix C: PWG recommendations

The PWG's recommendations reflect a balanced, long-term approach to managing solar installations at EOL, as outlined in the Eunomia systems options report, address stakeholder concerns, and ensure compliance with EOL management standards. The recommendations include a statewide Mixed Municipal Solid Waste (MMSW) disposal ban and recycling requirements:

- **MMSW disposal ban for all solar installations**: Prohibits landfilling, incineration, and improper disposal of solar installations, ensuring that all EOL materials are either reused (encouraged) or recycled (mandatory). This would include a ban on incineration and disposal beyond state lines and would keep valuable materials in the circular economy.
- **Statewide recycling requirements for all solar installations**: All installations, regardless of size, would need to meet recycling mandates. Larger installations would use existing decommissioning standards, while smaller installations would receive support from a newly established Central Management Organization (CMO) to ensure cost-effective compliance (see two approaches below):
  - **Approach A:** Decommissioning requirements for installations above 1 MW DC and co-located CSGs
    - Funded by permittees
    - Requires recycling
    - Lowers current decommissioning process from 50 MW DC to above 1 MW DC
    - Includes all co-located CSGs
    - Includes previous and future installations
    - Harmonizes decommissioning standards across jurisdictions
    - Implemented immediately
  - **Approach B:** Creation of a Central Management Organization (CMO) for installations 1 MW DC and below
    - Could be funded by one or multiple options: permittees, producers, wholesalers, rate payers, utilities
    - Requires recycling
    - CMO provides logistical and operational support to help small installations comply with recycling requirements
    - Implemented within 24 months

Recommendation: Statewide MMSW disposal ban

Scope and objectives

The PWG recommends implementing a MMSW disposal ban for all solar installations generated as waste in Minnesota. This ban applies to solar installations of any array size, location, or lifecycle stage, covering all potential discard scenarios, including damage during transport, installation, or other incidents before reaching their intended EOL. This ban aims to prevent mismanagement, illegal disposal, disposal within or outside of Minnesota, and environmental hazards by ensuring that all EOL solar installations are either reused (encouraged) or recycled (required). The PWG recommends the MMSW disposal ban take effect immediately or within twelve months following legislative approval (to provide the industry time for preparation).

To ensure comprehensive effectiveness, the PWG recommends extending this ban to include all forms of disposal, such as incineration or export for disposal outside of Minnesota. This measure ensures that all solar installations generated as waste within the state are managed under Minnesota's recycling requirements, thereby preventing circumvention of waste management objectives.

Given potential legal challenges related to interstate commerce laws, MPCA should consider developing creative regulatory strategies, such as tracking the weight and destination of materials or requiring companies to register and agree to comply with state policies. This approach would align with constitutional requirements while advancing Minnesota's waste management goals, drawing on practices already in use for e-waste management in the state. Importantly, this prohibition must not restrict solar installation owners from utilizing qualified out-of-state recyclers.

Exemptions

A majority of the PWG supports a "no exemptions" policy, ensuring that all solar installations are covered by this ban. In rare cases where solar installation components are considered 'non-recyclable' due to condition or technology, MPCA would handle these on a case-by-case basis with enforcement discretion. Some PWG members support a carefully worded exemption for solar installations that are considered non-recyclable. In such cases, MPCA would oversee the investigation of potential misuse and ensure enforcement of the exemption policy to prevent exploitation.

Enforcement and regulatory framework

The PWG recommends MPCA oversee enforcement of this MMSW disposal ban in collaboration with local government units (LGUs) and the Public Utilities Commission (PUC), potentially using enforcement mechanisms modeled after Minnesota's cathode-ray tube (CRT) prohibition[2]. This approach would follow the enforcement framework authorized by Minnesota Statute, Chapter 115A.034, which grants MPCA authority over waste management in Minnesota. Under current Minnesota regulation, MPCA allows solar installations to be managed equivalent to other e-waste; if they are shown to be recycled, they are exempt from hazardous waste requirements, including evaluation.

Recommendation: Statewide recycling requirements

Scope and objectives

The PWG recommends implementing recycling requirements for all solar installations generated as waste in Minnesota. While reuse is encouraged, it would not be required. These statewide recycling requirements would ensure that all solar installations, regardless of installation size or installation date, are responsibly managed to support sustainable material recovery and reduce environmental impact.

Recycling goals

The PWG agrees with the 2023 Minnesota Session Law (Laws of Minnesota 2023, chapter 60, article 3, section 36) that there should be a 100 percent take-back goal. Additionally, the PWG recommends setting a high-value recycling target within five years of this policy's implementation, aiming for at least 90 percent material recovery (by weight) in line with the European Committee for Electrotechnical Standardization (CENELEC) EN50625-2-4 and TS50625-3-5, Sustainable Electronics Recycling International (SERI) R2V3, or comparable United States or

[2] Minnesota Statutes, section 115A.9565. Effective July 1, 2006, a person may not place in mixed municipal solid waste an electronic product containing a cathode-ray tube.

international standards This goal should prioritize the recovery of valuable metals and materials, including silicon and other semiconductor materials, as well as high-quality glass, to advance a circular economy and sustainable material reuse.

Approaches to recycling

The PWG recommends meeting statewide recycling requirements in these ways, which are expanded upon below:

A. **Decommissioning requirements for installations above one MW DC and all co-located CSGs:** Solar installations in this category would be required to follow strict decommissioning requirements that include recycling mandates, financial assurances, and compliance with EOL management standards.
B. **A Central Management Organization (CMO) to support small installations one MW DC and under:** The CMO would provide logistical and operational support including recycling and reuse options, to ensure these smaller installations can comply with the state's EOL requirements.

Approach A: Decommissioning requirements

Current decommissioning requirements

Current decommissioning requirements for solar installations in Minnesota are not set in law or rule but are determined by site-specific permitting processes. For installations with a capacity 50 MW DC and above, decommissioning requirements are established at the state level and overseen by PUC. These requirements mandate that the site be restored to its original condition upon the retirement and removal of the facility. As part of the decommissioning process, permittees must:

- Outline how the site will be restored.
- Estimate the costs associated with decommissioning.
- Provide financial assurance to ensure the completion of the work.
- Update the decommissioning plan every five years to reflect current conditions and practices.

For installations below 50 MW DC, decommissioning requirements are regulated by counties, townships, or cities, with counties often taking the lead. While there is no standardized template for these requirements, they follow similar principles, including restoring the site to its original condition and requiring financial assurances, such as performance bonds, to ensure compliance. Coordination between LGUs and the PUC helps to support consistency in these practices, though variations exist due to local permitting conditions. More information on existing practices is available in the *Repowering and Decommissioning of Wind and Solar Energy Projec*t report (Great Plains Institute, 2020).

Recommended expansion of decommissioning requirements

Building on these existing requirements, the PWG recommends lowering the threshold for mandatory decommissioning requirements to include all installations over one MW DC, as well as for co-located CSGs of all sizes. Most of these installations are already subject to county-level decommissioning requirements as a condition of the project's land use permit. Broadening these requirements would ensure consistent EOL management across a broader range of projects effective immediately upon policy approval.

Permittee responsibilities: Under the recommended decommissioning requirements, solar installation permittees and owners would continue to be responsible for covering all recycling costs associated with EOL management. Decommissioning plans for these installations would continue to outline sustainable practices, require financial assurances that account for required recycling, and undergo updates every five years to maintain compliance with evolving standards.

Harmonized decommissioning standards across jurisdictions: The PWG recommends that existing installations of 50 MW DC and above integrate recycling obligations into their decommissioning plans during their regular five-year update. For existing installations between one and 50 MW DC as well as co-located CSGs, the MPCA, Commerce, LGUs, and/or the PUC would work collaboratively to harmonize decommissioning requirements, creating a unified regulatory approach statewide and replace fragmented or overlapping regulations. These agencies would also offer technical support for the integration of these new recycling requirements.

To minimize financial burdens on solar installations installed before the effective date of this legislation, the PWG suggests providing incentives, such as grants or subsidies to reduce individual project costs. This approach would help achieve consistency across installations statewide, minimize potential taxpayer liabilities, and promote compliance.

Alternative perspective on legacy installations: The Minnesota Solar Energy Industries Association (MnSEIA) prefers that permittees of solar installations installed before the effective date of this legislation be exempt from any costs incurred for recycling under the proposed systems. This is important to MnSEIA because a retroactive change to contracts already signed could have further implications on a number of matters impacting permittees and consumers. This includes financing agreements and other contractual obligations for installations that predate these proposed systems. The responsibility for proper disposal of those system components would fall on the system owner, as it currently does. MnSEIA suggests that the CMO create and manage a database of all existing solar installations that may be eligible for any exemption of this type. Permittees would need to prove that their solar installation was installed before the effective date of this legislation and request that the CMO include it in its database or otherwise approve of its exemption.

Approach B: Creation of a CMO

The PWG recommends the establishment of a CMO to oversee and facilitate the EOL management of solar installations one MW DC and under. Larger installations could also opt to participate, in order to gain access to collective resources that reduce individual costs. However, this participation would not allow larger installations to shift financial responsibility for recycling costs to a solar panel manufacturer, producer, or wholesaler, so that financial responsibility would remain with the permittee. The PWG recommends that the CMO begin operation within 24 months of this policy's approval, ensuring that smaller installations have a workable path to compliance as the statewide recycling mandate takes effect.

Development of the CMO by a working group

The PWG recommends a dedicated working group be created to guide its formation, in order to ensure the CMO aligns with the state's goals and stakeholder interests, and to provide transparency, accountability and broad-based input in the planning process. The working group would include representatives from industry, government, utilities, recyclers, Tribal governments, and environmental organizations. Its primary responsibilities would be to recommend to the legislature a governance structure, financial model, oversight, and reporting and metrics requirements for the CMO. The working group would also recommend whether the CMO would be a private entity, a state agency, or a nonprofit organization like a Producer Responsibility Organization (PRO). The working group would dissolve after making the recommendations to the legislature.

Responsibilities of the CMO

The PWG recommends the CMO handle these, and any other activities deemed necessary by the working group:

- **Support for small installations:** The CMO would provide guidance and resources to solar installations one MW DC and under, helping them identify recycling (required) or reuse (encouraged) options for their solar installations at EOL. The CMO would ensure that these solar installations are collected, transported, and processed either through approved in-state or out-of-state recyclers or reuse companies.

- **Maintain vetted resource list:** The CMO would develop and maintain a vetted list of registered collectors, recyclers, and reuse companies that is updated on an ongoing basis. This registry would uphold management standards set by the U.S. Environmental Protection Agency (EPA) and establish criteria for addition to the list that prevents improper disposal or mismanagement of solar installations at EOL.
- **Issuing RFPs for EOL services:** To ensure high-quality deinstallation, collection, reuse, and recycling, the CMO would have the authority to issue Requests for Proposals (RFPs) to vetted providers of recycling services and would work with the MPCA to develop standards to ensure recyclers follow industry best practices and handle materials safely. This process would foster competitive, innovative, and reliable services and enable installations to access cost-effective solutions for panel decommissioning.
- **Issuing certificate of recycling:** The CMO would issue certificates of recycling on behalf of recyclers to parties that supplied the panels for recycling. These certificates would serve as formal documentation to confirm proper EOL management and support compliance with regulatory and contractual obligations.

Funding mechanisms for the CMO

The PWG recommends that funding for the CMO come from one or a combination of contributions, including permittee fees, and/or support from producers, wholesalers, ratepayers, and/or utilities. The Value of Solar Tariff[3] (VOST) could also be modified to support the CMO as a sustainable funding mechanism.

Stakeholder contributions: Based on an informal survey of PWG member organizations results (N = 21 or 87.5 percent) indicated varying levels of support for potential funding sources among PWG participants:

- **Permittees:** 85.7 percent of PWG participants supported contributions from system owners and operators.
- **Wholesalers:** 85.7 percent of PWG participants indicated support for wholesaler contributions.
- **VOST:** 71.4 percent of PWG participants supported the inclusion of VOST as a funding source.
- **Producers:** 60.4 percent of PWG participants indicated support for producer contributions.

Permittee fees: Based on PWG discussions following the informal survey, it was suggested that if permittee fees are included there should be flexible payment options including:

- **Upfront payment** at the time of installation, providing early financial resources for CMO operations. To ensure accuracy, recycling costs would need to be reassessed regularly to reflect the most up-to-date estimates.
- **EOL fee** applied at the time of panel decommissioning, rather than when solar installations are dropped off at a collection site, ensuring that fees are collected.
- **Lifecycle payments** distributed across the operational lifespan of the solar installations, allowing for manageable, ongoing contributions to the CMO's budget. This option would be phased out after a set number of years in order to not disincentivize older installations. This option received the most support from PWG members in discussions about permittee fees.

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[3] Value of Solar Tariff (VOST) is a rate structured designed to compensate solar energy producers based on the value their electricity provides to the grid, considering factors such as energy production, environmental benefits, grid reliability, and avoided infrastructure costs.

Reuse considerations

Not all solar installations would be suitable for reuse for a variety of reasons, including requirements by permittee or panel manufacturer to prioritize recycling. The PWG did not support a reuse requirement unless the following needs could be addressed:

- **Testing protocols and equipment:** The industry requires low-cost, portable rapid testing protocols and equipment to quickly assess the electrical and structural integrity of solar installations in order to determine whether reuse is a viable option.
- **Standardized deinstallation and transport:** Standardized protocols and equipment are needed for deinstallation, transport, and storage. These standards should prioritize safety, minimize handling and potential damage, and reduce associated costs, ensuring a streamlined and cost-effective process.
- **Pricing models for financial viability:** A pricing model is needed to balance the cost of handling reused solar installations with the potential electrical income they could generate when returned to service, in order to provide a competitive and financially attractive alternative to recycling.
- **Safeguards against improper disposal:** Safeguards must be in place to ensure that reused panels, especially those shipped out of state, are not landfilled or improperly disposed of. Compliance mechanisms are needed to prevent environmental harm and support sustainable reuse practices.
- **Cost responsibility:** To ensure fairness and compliance, any costs related to testing, transportation, de-installation, or other reuse activities should remain the responsibility of the permittee. These costs must not be shifted to the manufacturers, who are not involved in reuse-related processes.

By addressing these considerations, the PWG concluded that reuse of solar installations could be a viable component of EOL management while ensuring safety, compliance, and financial sustainability.

Financial incentives

The PWG recommends developing financial incentives to support development of recycling technology and infrastructure and to encourage sustainable EOL management for solar installations across Minnesota, especially in rural areas, Tribal communities, and areas in need of environmental justice. These incentives, which may include tax credits, grants, and subsidies, would promote investment in Minnesota-based recycling facilities, transportation costs, and help installations comply with EOL requirements in a cost-effective way.

The PWG emphasizes that these incentives are not intended to be ongoing subsidies. Instead, they are designed to accelerate the expansion of critical recycling infrastructure, support existing installations in transitioning to compliant practices, and promote stakeholder participation. This proactive approach would reduce the risk of future clean-up costs, which could put a significant financial burden on taxpayers.

Although the policy could move forward without these incentives, the PWG believes they are critical to the effectiveness of the statewide solar installation recycling mandate by reducing financial burdens on stakeholders. The PWG encourages the exploration of public and private partnerships to fund these incentives, thereby supporting Minnesota's commitment to a sustainable, circular economy.

Financial considerations for whole system recycling

The study legislation covers EOL management for all solar photovoltaic modules and installation components. The PWG noted that installation components are not produced by solar panel manufacturers. Therefore, some PWG members representing solar panel manufacturers wanted to ensure that any recycling mandate does not shift recycling costs for installation components onto solar panel manufacturers.

Appendix D: Legislative charge

MN Solar report final language 2023
HF2310, Chapter 60 Session Laws

ARTICLE 1

ENVIRONMENT AND NATURAL RESOURCES APPROPRIATIONS

Sec. 2. **POLLUTION CONTROL AGENCY**

Subd. 7.**Resource Management and Assistance**	82,000,000	57,974,000
Appropriations by Fund		
	2024	2025
General	38,464,000	13,850,000
Environmental	43,536,000	44,124,000

(m) $420,000 the first year is to complete a study on the viability of recycling solar energy equipment. This is a onetime appropriation and is available until June 30, 2026.

ARTICLE 3

POLLUTION CONTROL

Sec. 36. **REPORT REQUIRED; RECYCLING AND REUSING SOLAR PHOTOVOLTAIC MODULES AND INSTALLATION COMPONENTS.**

(a) The commissioner of the Pollution Control Agency, in consultation with the commissioners of commerce and employment and economic development, must coordinate preparation of a report on developing a statewide system to reuse and recycle solar photovoltaic modules and installation components in the state.

(b) The report must include options for a system to collect, reuse, and recycle solar photovoltaic modules and installation components at end of life. Any system option included in the report must be convenient and accessible throughout the state, recover 100 percent of discarded components, and maximize value and materials recovery. Any system option developed must include analysis of:

(1) the reuse and recycling values of solar photovoltaic modules, installation components, and recovered materials;

(2) system infrastructure and technology needs;

(3) how to maximize in-state employment and economic development;

(4) net costs for the program; and

(5) potential benefits and negative impacts of the plan on environmental justice and Tribal communities.

(c) The report must include a survey of solar photovoltaic modules and installation components that are currently coming out of service and those projected to come out of service in the future in Minnesota. The report must include a description of how solar photovoltaic modules and installation components are currently being managed at end of life and how they would likely be managed in the future without the proposed reuse and recycling system.

(d) After completing the report, the commissioner must convene a working group to advise on developing policy recommendations for a statewide system to manage solar photovoltaic modules and installation components. The working group must include, but is not limited to:

(1) the commissioners of commerce and employment and economic development or their designees;

(2) representatives of the solar industry and electric utilities;

(3) representatives of state, local, and Tribal governments; and

(4) other relevant stakeholders.

(e) By January 15, 2025, the commissioner must submit the report and the policy recommendations developed under this section to the chairs and ranking minority members of the legislative committees and divisions with jurisdiction over environment and natural resources policy and finance and energy policy and finance.

Appendix E: Eunomia Research and Consulting. Final Report: *Solar PV Panel Reuse and Recycling Study; Developing a statewide system to reuse and recycle solar photovoltaics in Minnesota.* February 2025.

eunomia

Final Report: Solar PV Panel Reuse and Recycling Study

Developing a statewide system to reuse and recycle solar photovoltaics in Minnesota

February 2025

Report For

MINNESOTA POLLUTION CONTROL AGENCY

Project Team

eunomia

PRODUCT STEWARDSHIP INSTITUTE

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Executive Summary

In 2023, the Minnesota State legislature directed the Minnesota Pollution Control Agency (MPCA) to commission a study on 'RECYCLING AND REUSING SOLAR PHOTOVOLTAIC MODULES AND INSTALLATION COMPONENTS,' via Session Laws Chapter 60, Article 1, Section 2, Subd 7(m), and Article 3, Section 36.' The MPCA secured the services of Eunomia Research and Consulting, Inc. (Eunomia) with support from the Product Stewardship Institute (PSI) to develop this study.

The enabling statute also requires MPCA to convene a Policy Working Group (PWG), with members representing a cross-section of interests, to advise the agency on policy recommendations for system options intended to meet the criteria and analyses outlined in the study legislation. The Solar PV Panel Reuse and Recycling Study will be used by the PWG to advise the MPCA on developing policy recommendations which the MPCA will submit to the Minnesota Legislature by January 15, 2025, for the preferred statewide system for solar equipment end-of-life management.

Policy Options and Evaluation

The project team's first step in determining what scenarios to model built upon the work MPCA had already performed to narrow down policy options. Since 2019, MPCA has worked with a broad group of stakeholders (e.g., hosting workshops and implementing surveys) to identify policy solutions for the end-of-life (EOL) management of solar PV panels. From this work, MPCA and stakeholder participants had determined nine policy objectives (see Figure 1) and identified four potential policy solutions:

(1) extending decommissioning plan requirements for utility and commercial PV facilities under 50MW,
(2) a product stewardship program,
(3) a ratepayer funded program, and
(4) a permittee funded program.

After completing a full review of MPCA's previous work to determine policy options, a literature review, interviews with stakeholders along the solar PV panel value chain, and internal workshops, the project team added two additional policies for consideration in this study:

(5) landfill bans, and
(6) targets for collection, reuse, and recycling.

For each of these six policy options, Eunomia conducted a thorough evaluation of each policy against a set of criteria developed to align with MPCA's policy goals and incorporated the project team's expertise on best practices for managing EOL products. Table 1 below summarizes how each policy option performed against the evaluation criteria. Green indicates the policy achieves best practice for this criterion, yellow indicates that the policy can integrate this through policy design or implementation to meet the best practice, and red indicates that the policy does not meet best

Figure 1. MPCA's Solar PV Panel EOL Management Policy Goals

1. Create a statewide program and sustainable funding mechanism that does not require a fee at the time of disposal/recycling.
2. Require recycling and reuse of end-of-life solar PV panels and include a disposal ban.
3. Encourage sustainable materials and design of solar PV panels by manufacturers.
4. Internalize costs to the project or developer.
5. Does not disadvantage anyone in the Minnesota solar PV panel market regarding costs.
6. Achieve consistency and predictability.
7. Applies to all solar PV panels installed in Minnesota, from residential-scale to utility-scale projects.
8. Reduce national security concerns associated with dependence on other countries for scarce critical materials and finished products.
9. Sustainable end-of-life program funding source(s) associated with solar energy activities.

practice for this criterion. A deeper dive into the criteria and how each policy was evaluated is included in Section 2.1 and Section 2.2 of this report.

Table 1. Policy Options Evaluation Summary

Evaluation Criteria	Recycling and reuse targets	State utility scale decom-missioning program	Landfill ban on PV panels	Permittee-funded statewide program	Ratepayer-funded statewide program	EPR / Product Stewardship program
Covers all PV types and includes residential, commercial, and utility installations						
Funding mechanism **internalizes costs** of managing PVs at EOL						
Includes funding to establish **organized collection** of PVs at EOL						
Includes funding for **investment in infrastructure and R&D**						
Establishes measurable **performance targets** for collection, reuse, and recycling						
Encourages **design for recycling** and/or reuse						

Stakeholder Input

The project team conducted multiple workshops and held interviews with EOL solar PV panel stakeholders, including solar manufacturers, installers, recyclers, industry and community associations, local and state governments, and Tribes in Minnesota. Interviewees were asked about the need for EOL solar PV panel policies, the policy options being considered for Minnesota and any data or insight they may have for the modeling exercise. Stakeholder input shaped the assumptions used in the model design and the policy scenarios that were ultimately put forward to be modelled.

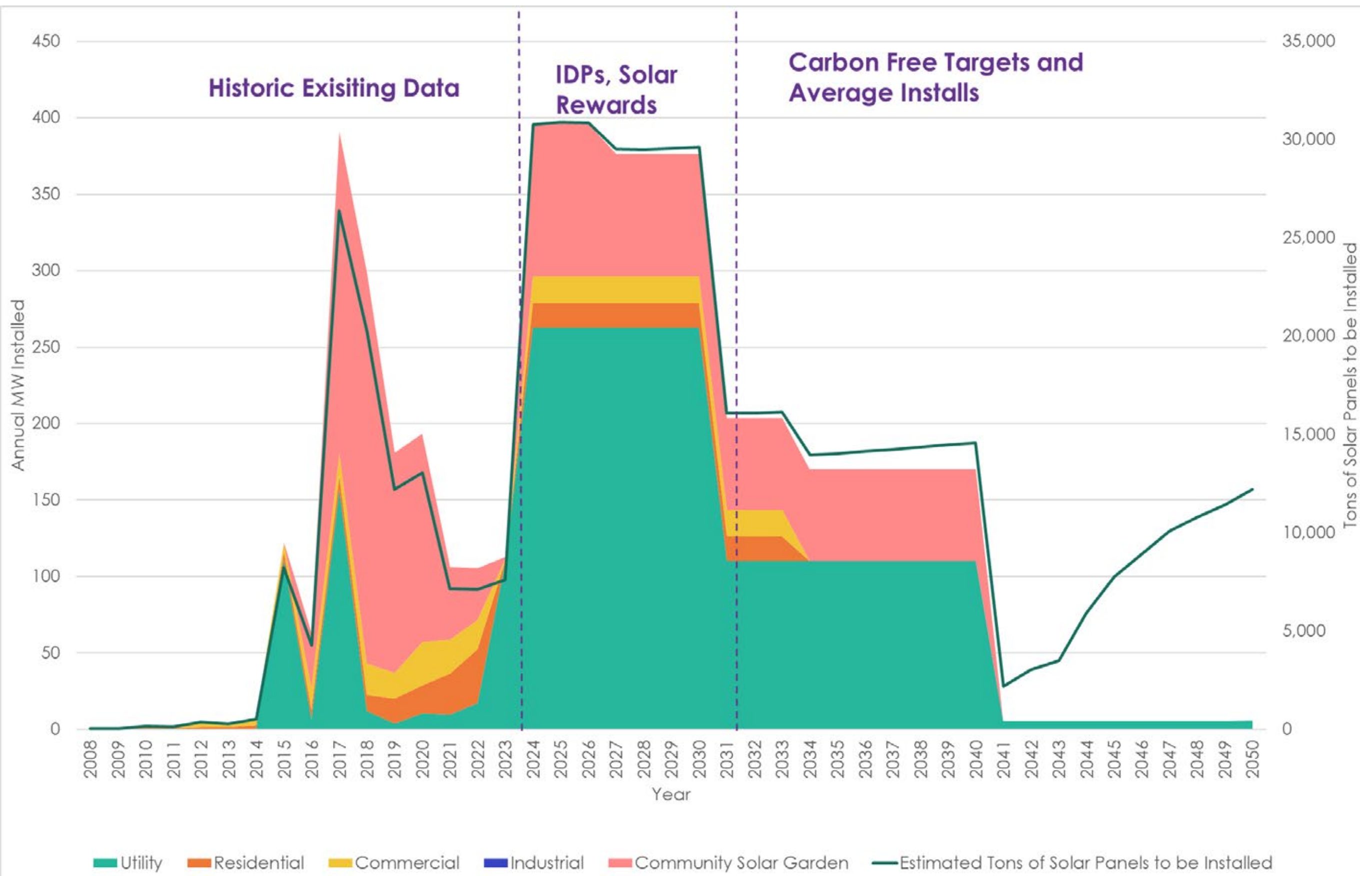
All interviewees agreed that there is a need to address the future volume of solar PV panels that will need EOL management. Interviewees' thoughts on the policy scenarios varied by stakeholder group and by the solar PV panel sector to which the policies would apply (i.e., residential vs. utility). A summary of key feedback from stakeholders is included in Section 2.3 of this report. Important to note, EOL solar PV panel stakeholders will have additional opportunities (if members of the Policy Working Group (PWG)) to input their feedback as the MPCA builds upon the findings in this report to develop the policy recommendations that will ultimately be submitted to the Minnesota Legislature in 2025.

Installation Forecasting and End of Life Estimates

The project team's first step in their modelling approach was to evaluate the level of end of life (EOL) solar PV panels that are currently generated in Minnesota and to forecast the expected number of PV panels that will reach EOL from 2024-2050. This was done using both primary and secondary research which is detailed in Section 3.2.1 of this report. With this research the project team was able to estimate EOL generation, by first compiling historic installation in the state of Minnesota, and subsequently projecting future installations until 2050. After doing so, the project team was able to apply useful lifetime assumptions to these installations.

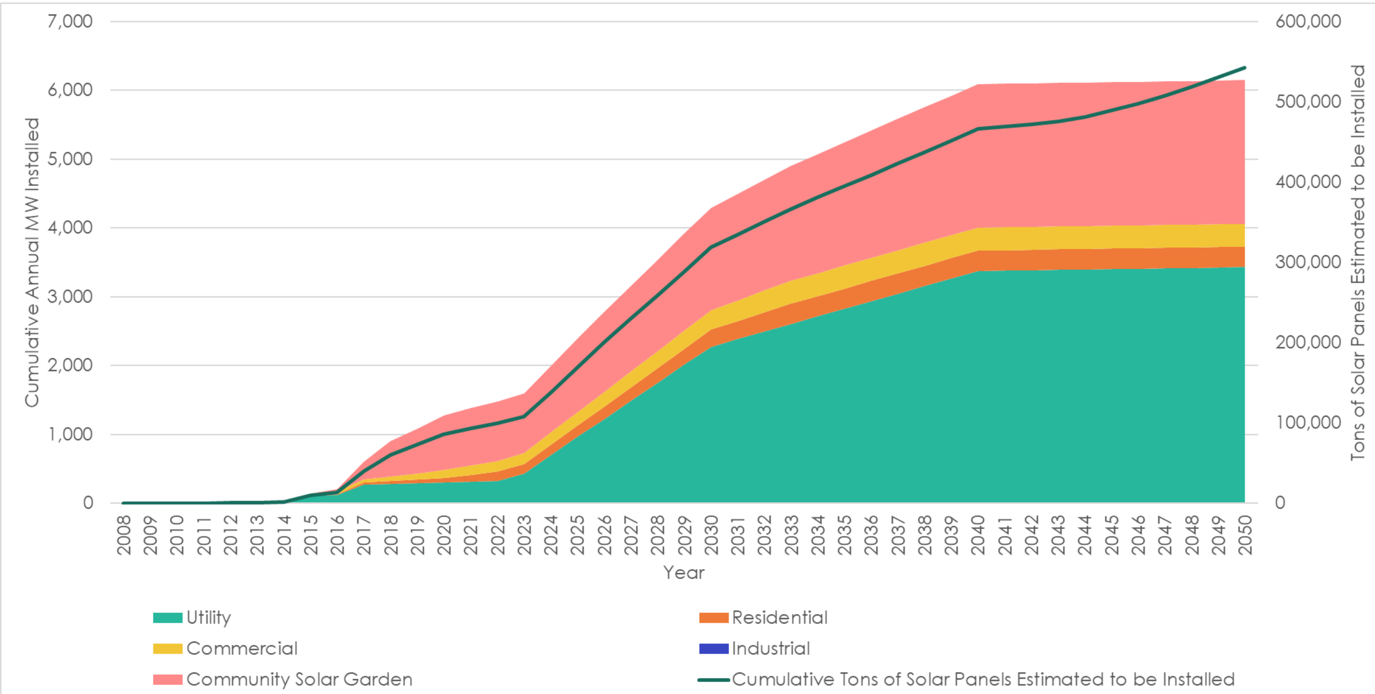
The modelling team estimated the total MWs of solar to be produced in MN from 2024-2050 using a combination of state clean energy and solar targets, utility company integrated distribution plans (IDPS) and historical data on the average MWs per year of solar installed in MN. This forecasting is split into two periods, 2024-2030 and 2031-2050, as a result of utility companies having announced their installation forecasts up to 2030 and a 10% solar target for utility companies to meet in 2030, with "Carbon Free" electricity goals set after 2030. These forecasting methods are outlined in detail in Section 3.2.2.2 of this report. Figure 2 shows a summary of all existing and project annual solar installations, along with the predominant estimation method against the tons of solar PV panels estimated to be installed and Figure 3 shows the cumulative annual solar capacity from 2008-2050.

Figure 2. Annual Installed Solar Capacity 2008-2050



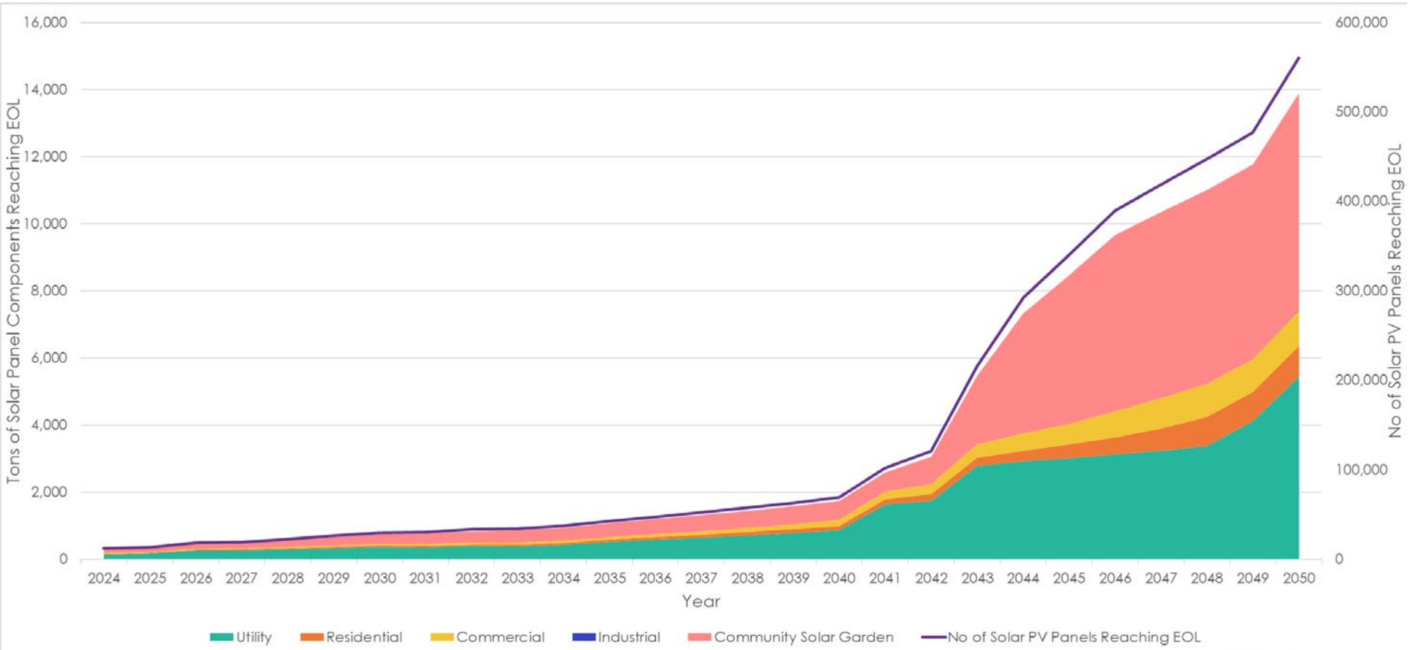
In the forecasted installation, the drivers for new installations and capacity expansion after 2040 are not well defined and therefore have been assumed to be minimal for new capacity. The area chart shows the MW installed of new solar capacity, while the green line shows the tons of solar panels installed including new *and* replacements for existing capacity. This is why the line increases again after 2041, as replacements for panels are installed, while no new capacity is added.

Figure 3. Cumulative Installed Solar Capacity 2008-2050



To estimate how many solar PV panels will reach their end of life from 2024-2050, the previously gathered and calculated historical and forecasted solar tonnage data was entered into an average lifespan matrix. Section 3.2.3 outlines various assumptions made within this matrix and Figure 4 shows the results from this forecasting approach against the estimated number of solar panels expected to come offline on the right axis. Annual EOL solar PV panels begin to arise in greater numbers after 2040. Community solar garden scale panels make up the majority of tons of solar PV panels reaching EOL. At their peak in 2050, over 14,000 tons of solar PV panels reach end of life each year. The number of solar panels detaches slightly from the trend of tons of solar panels as panel weights are assumed to decrease over time, increasing the capacity per ton installed.

Figure 4. Projected Tons of Solar PV Panels Reaching End of Life



Scenario Modelling

After evaluating the policy options and incorporating additional context from stakeholders across the value chain, the project team and MPCA determined five policy scenarios, plus a baseline "no new policy" scenario, to model within this study. Underlying each scenario is a set of key design assumptions used in the modeling process. These assumptions show the different mechanics for how EOL solar PV panels are collected and what happens to them post-collection. Each scenario and its underlying assumptions are summarized in Table 2.

Table 2. Overview of Scenarios Modelled and Key Assumptions for Each

	No New Policy	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Short Description	**No policy except existing decommissioning (>50MW)**	**Lower Decomm threshold w/recycling requirement (e.g. >1MW); Disposal ban for all**	**Lower Decomm threshold w/recycling requirement; Disposal ban for all; recycling targets <1MW**	**Permittee/Owner pays; Decomm reqmts >1MW, Disposal ban and recycling requirements for all**	**Full EPR to manage all panels; Decomm reqmts >1MW; Disposal ban and recycling requirements for all**	**Decomm/recycle requirements for utility only, EPR for all other installations; Disposal ban for all**
By Sector						
Utility	Decommissioning (>50MW)	Decommissioning/ recycling >1MW; Disposal ban	Decommissioning/ recycling >1MW	Decommissioning/ recycling >1MW	Full EPR (All Capacity) Decommissioning >1MW	Decommissioning/ recycling >1MW
Residential	No New Policy	Disposal ban	Landfill Ban with Targets	Permittee	EPR	EPR
Commercial	No New Policy	Disposal ban	Landfill Ban with Targets	Permittee	EPR	EPR
Industrial	Decommissioning (>50MW)	Decommissioning/ recycling >1MW; Disposal ban	Decommissioning/ recycling >1MW	Decommissioning/ recycling >1MW; Permittee	EPR	EPR
Community Solar Garden	No New Policy	Decommissioning/ recycling >1MW; Disposal ban	Decommissioning/ recycling >1MW Landfill Ban with Targets	Decommissioning/ recycling >1MW; Permittee	EPR	EPR
Key Assumptions						
Large Volume Collection	Bulk pickup	Bulk pickup	Bulk pickup	Bulk pickup	Bulk pickup	Bulk pickup
Small Volume Collection	None	Public or Private Depots	Public or Private Depots	Dedicated (modelled at one per county)	Dedicated (modelled at one per county)	Dedicated (modelled at one per county)
Transportation – Large Volume	Direct to Recycler	Direct to Recycler	Direct to Recycler	Direct to Recycler	Direct to Recycler	Direct to Recycler
Transportation – Small Volume	None	Bulking Center then recycler	Bulking Center then recycler	Bulking Center then recycler	Bulking Center then recycler	Bulking Center then recycler
Recycler Location – Large Volume Sites	Out of state for large	Out of state	Out of state	Out of state	Out of state until enough volume for Minnesota	Out of state until enough volume for Minnesota

	No New Policy	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Recycler Location – Small Volume Sites	Minnesota	Minnesota	Minnesota	Minnesota	Minnesota	Minnesota
Level of Recycling	Limited*	Limited for panels above threshold, hazardous disposal for others	Comprehensive** for all but utility sector	Modeled with: limited for all; and comprehensive for all	Comprehensive for all	Comprehensive for all but utility sector
Program Management	N	N	N	Y	Y	Y

*Limited recycling refers to glass and aluminum recovery only and is at a 98% glass recovery yield and a 94% yield for aluminum,[1] no other materials are recovered. The overall yield is around 80%.
**Comprehensive recycling refers to maximum recovery of all materials and averages at a 91.90% yield for silicon panels.[2]

The designation between scenarios with limited and comprehensive recycling is related to which scenarios best represent the current situation with weight-based targets in the EU, where facilities are recovering only glass and aluminum to meet recycling targets that are not sufficient to drive recovery of other metals and semiconductor materials by weight or value.[3] .This is discussed further in Section 2.2. Section 3.0 of this report provides an in-depth description of all the modeling methodology, including data sources and assumptions underlying each scenario. The project team utilized both primary and secondary research and information from stakeholder experts to develop the generation, installation, and forecasting model.

Costs

Annual Net Costs

Total System Net Costs include initial collection costs, consolidation costs, recycler transportation costs, dismantling/recycling costs, and program management costs. Deinstallation costs are not included in Total System Net Costs as Eunomia assumed that EOL solar PV panels would have to be uninstalled regardless of whether they were going to be recycled or going to landfill. Additionally, since the purpose of policy is to ensure that materials are taken to recycling, all scenarios except for the No New Policy Scenario require 100% collection. This means that even scenarios without policies devoted to specific sectors have costs to manage solar PV panels.

Figure 5 illustrates the costs for each scenario alongside the total tons of solar PV panels reaching EOL from 2024 to 2050. The lines in the chart represent the annual net cost for each scenario, while the bar graph shows the total tons of solar PV panels reaching EOL each year. This chart shows how the cost of each system is dependent on the number of panels reaching end of life. However, there are still differences in the cost of the scenarios as each scenario recycles different quantities of solar panels, leading to differences in total cost.

Costs are highest in 2050, as the largest number of solar PV panels are coming offline this year. Scenario 4 (Full EPR) presents the highest total system costs of ~$12.1 million in 2050 followed by Scenario 3b (Permittee with Comprehensive Recycling Process) which costs ~$12 million in 2050 and Scenario Landfill Ban with Targets] which has costs of ~$10.6 million.

Figure 5. Total System Net Costs and Tons of Solar PV Panels Reaching EOL from 2024-2050

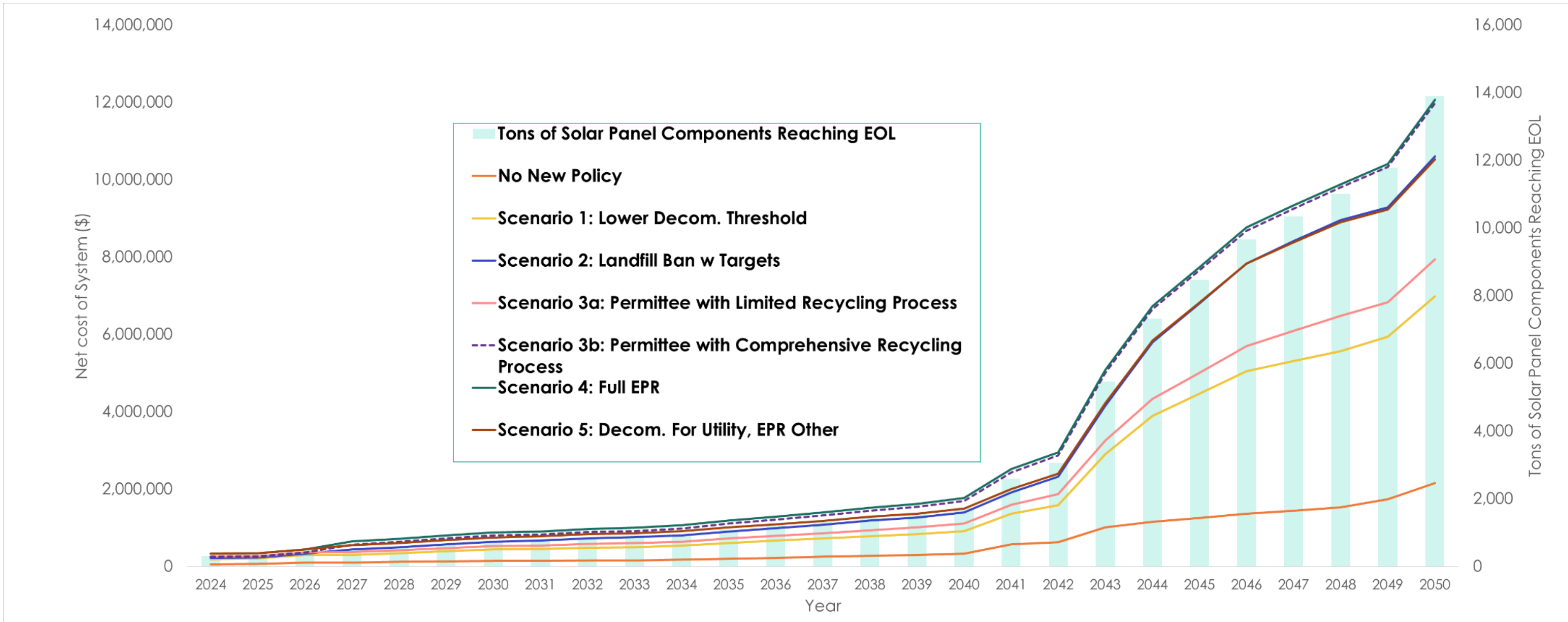
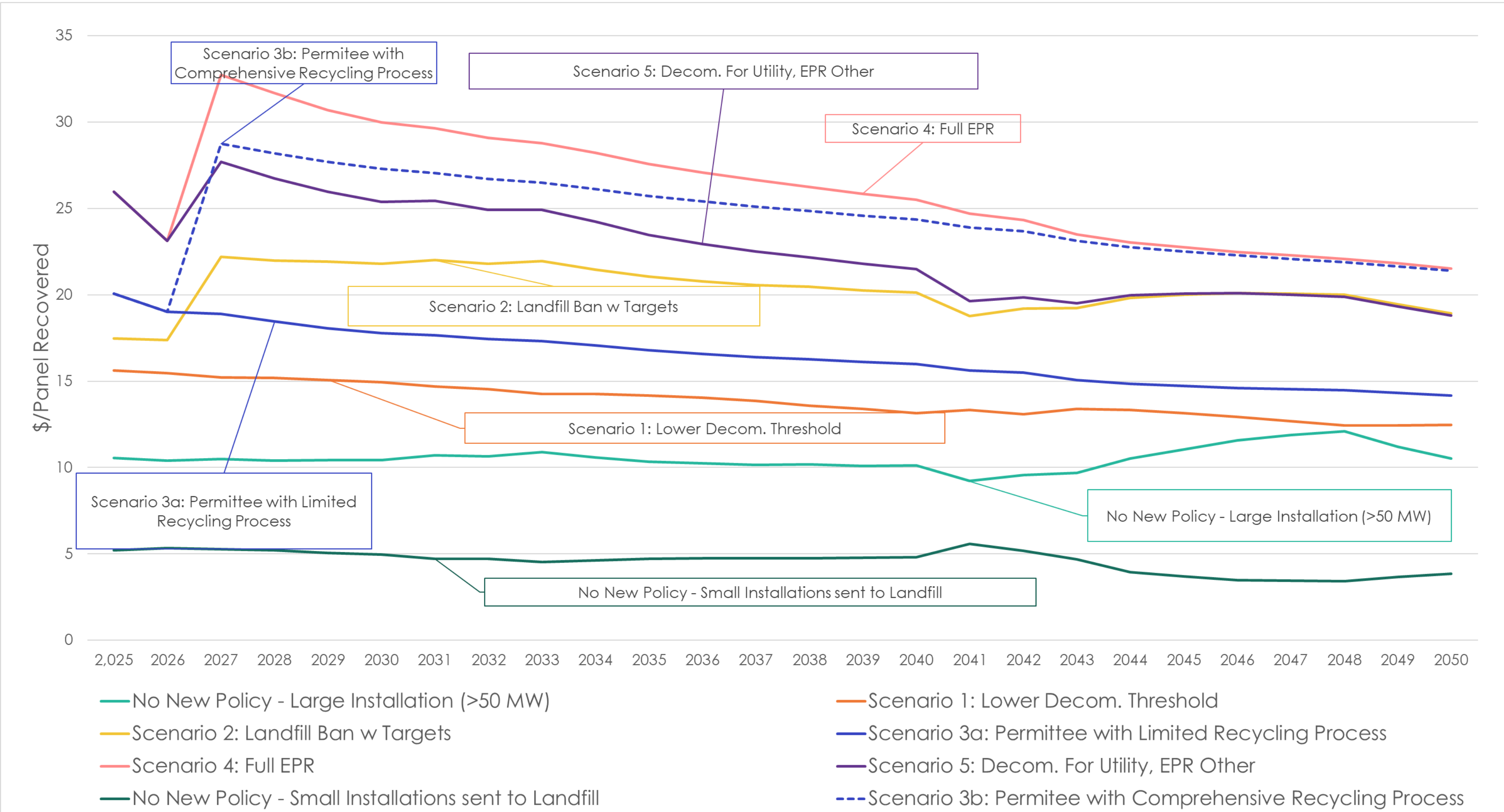


Figure 6 shows the annual costs per panel recovered for each scenario, from 2025 to 2050. In each of the scenarios with policy, the cost per panel line is smoother and has a slight decrease over time as the cost to recycle panels decreases. The no new policy scenario has a much more varied cost, as the cost per panel is reliant on panels from solar installations greater than 50 MW coming offline.

Figure 6. Cost per Panel Recovered by Scenario



Costs by Activity

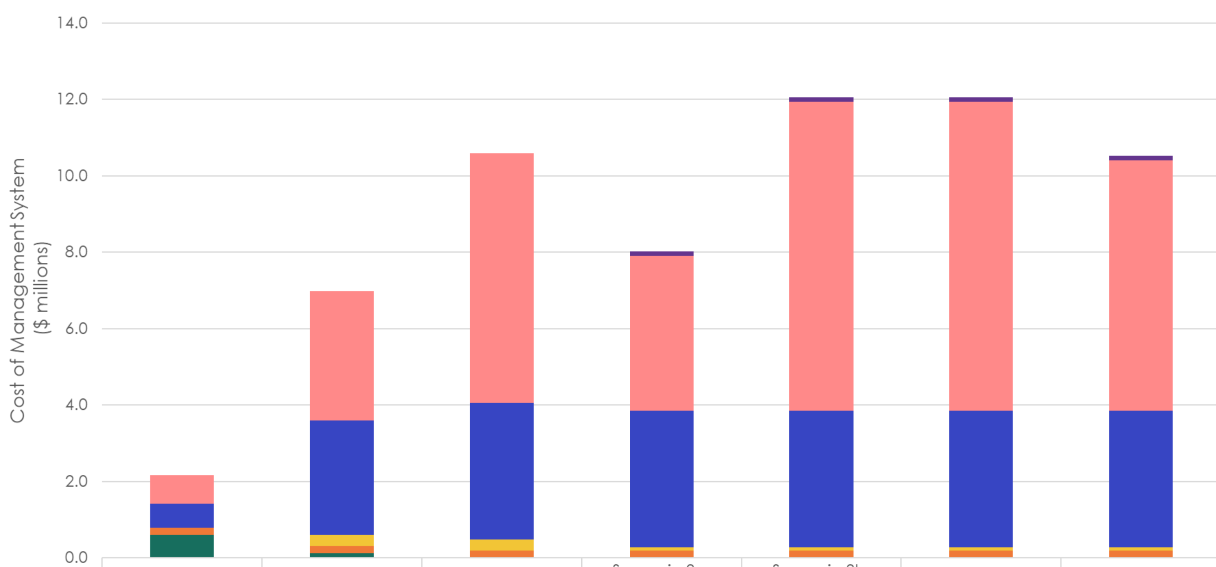
The five main modules of costs listed below were included in the estimate of EOL solar PV panel management.

- Initial collection of solar PV panels
- Transportation to recycler
- Depot reception of solar PV panels
- Solar PV panel recycling/dismantling
- Program management costs

A detailed outline of how the project team calculated each of these costs and key assumptions used in these calculations can be found in Section 3.3 of this report.

Figure 7. Total Cost by Activity in 2050

Figure 7 shows the total costs of the recycling system for 2050 for each modeled scenario. The costs are broken down by each of the activities mentioned in the list above. Note that there is an estimated $600,000 for disposal of solar panels from all sectors in the ‘No New Policy’ baseline. See Section 3.4.1, Table 30 for details.



	No New Policy	Scenario 1: Lower Decom. Threshold	Scenario 2: Landfill Ban w Targets	Scenario 3a: Permittee with Limited Recycling Process	Scenario 3b: Permittee with Comprehensive Recycling Process	Scenario 4: Full EPR	Scenario 5: Decom. For Utility, EPR Other
Program Management	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Recycling	0.7	3.4	6.6	4.0	8.1	8.1	6.6
Recycler Transportation	0.6	3.0	3.6	3.6	3.6	3.6	3.6
Depot Reception	0.0	0.3	0.3	0.1	0.1	0.1	0.1
Initial Collection	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Disposal	0.6	0.1	0.0	0.0	0.0	0.0	0.0

In all scenarios, the greatest cost to the system in 2050 is the actual recycling process of the solar PV panels. This varies from ~$1.3 million in the no new policy scenario to ~$8.1 million in Scenario 3b [Permittee with Comprehensive Recycling Process] and Scenario 4 [Full EPR]. The other costs remain relatively stable, as the logistics of the system are similar across scenarios. The exception is in depot reception costs, which are higher for the smaller quantities of residential and commercial panels. Scenarios with more comprehensive recycling such as the Landfill Ban with Targets, Full EPR, and Decommissioning for Utility, EPR Other have higher costs between ~$10 and ~$12 million each. Recycling transportation is similar in each scenario as all panels must be sent for recovery.

These costs are placed on a cost per panel and cost per ton basis in in Table 3. The table also shows the cost to de-install panels. While this is not explicitly a recycling cost and would likely not be covered under policy, it gives a sense of the relative size of the recycling-based costs versus the de-installation costs which would have to occur.

Table 3. Cost per Panel and Cost per Ton by Activity in 2050

	Cost per Panel							Cost per Ton						
	No New Policy	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**	**No New Policy**	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**
De-Installation	103	103	103	103	103	103	103	4,147	4,147	4,147	4,147	4,147	4,147	4,147
Recycling Activities Attributable to Policy:														
Initial Collection	0.0	0.4	0.3	0.3	0.3	0.3	0.3	0.0	15	14	15	14	14	14
Depot Reception	0.0	0.6	0.5	0.2	0.2	0.2	0.2	0	25	23	8	8	8	8
Recycler Transportation	6.4	6.4	6.4	6.4	6.4	6.4	6.4	135	250	283	299	274	274	283
Recycling	7.5	7.5	11.7	7.2	14.4	14.4	11.7	149	284	519	338	620	620	519
Program Management	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0	0	0	11	10	10	10
Total Recycling Activities	**13.9**	**15**	**19**	**14**	**22**	**22**	**19**	**285**	**574**	**840**	**670**	**926**	**926**	**835**

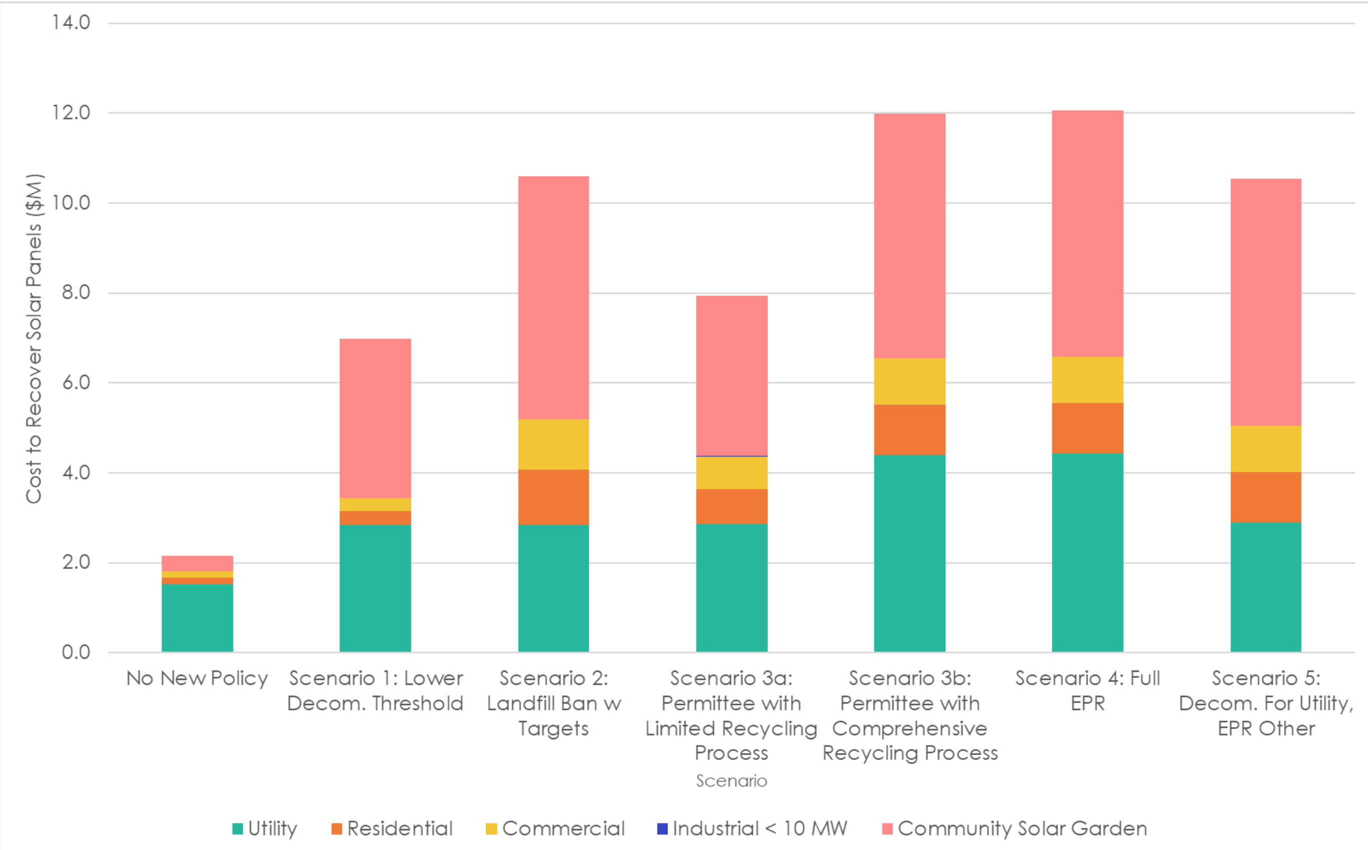
The full program cost per panel for recovery and recycling in 2050 ranges from $14-$22 per panel for scenarios with new policy. The full program cost per ton for recovery and recycling ranges from $638 to $926 per ton. Recycling alone varies from $7-$14 per panel, and $149-$620 per ton. Program management represents only $0.2 per panel recovered in the highest cost scenario, and $9 per ton. Note that under ‘No New Policy’ the cost per panel only applies to the Utility sector panels that are being recovered and recycled. In Scenario 1 the cost per panel applies to the panels being recovered from installations over 1MW in size and a small number of panels from smaller installations. The data in all tables and figures reflect the higher cost to collect and consolidate small numbers of panels from residential and commercial installations, as described in Sections 3.3 and 3.4.

Costs by Sector

The total annual cost in 2050 for each sector in each scenario is shown in Figure 8. The five sectors were categorized as the generators for EOL solar PV panels as listed below:

- Utility
- Commercial
- Residential
- Industrial
- Community Solar Garden (CSG)

Figure 8. Total Annual Costs by Sector in 2050



In each scenario that includes policy, CSGs represent the greatest total cost to the system. This is driven primarily by two factors:

- CSGs have historically had the most installations of any sector, and thus have the most volume.
- CSG installations are generally above 1 MW and are likely to be taken to a more national recycler out of state for comprehensive recycling.

Utility sector total costs are about $2.8 million in Scenarios 1, 2, 3a, and 5 with limited recycling, and about $4.4 million in Scenarios 3b and 4 with comprehensive recycling. Residential and commercial sectors together have total costs of about $2 million in scenarios 2, 3b, 4, and 5 with comprehensive recycling, and about $1.5 million in Scenario 3a with limited recycling. See section 3.4 for additional details.

Table 4 below shows cost per panel and cost per ton for each sector under each scenario. These are illustrated graphically in Figure 9 and Figure 10.

Table 4. Cost per Panel and Cost per Ton of Recovering Solar PV Panels in 2050, by Sector

	Cost per Panel ($/Panel)							Cost per ton ($/Ton)						
	No New Policy	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling Process**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**	**No New Policy**	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling Process**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**
Utility	13.9	14	14	14	21	22	14	285	606	606	610	861	867	616
Residential	*	*	26	17	24	24	24	*	*	1,402	984	1,288	1,296	1,296
Commercial	*	*	26	17	24	24	24	*	*	1,121	787	1,031	1,037	1,037
Industrial < 10 MW	*	15	22	15	22	22	22	*	862	1,176	867	1,180	1,188	1,188
Community Solar Garden	*	13	20	14	21	21	21	*	638	894	642	897	904	904

** No panels/tons recycled.*

Figure 9. Cost per Panel of Recovering Solar PV Panels in 2050, by Sector

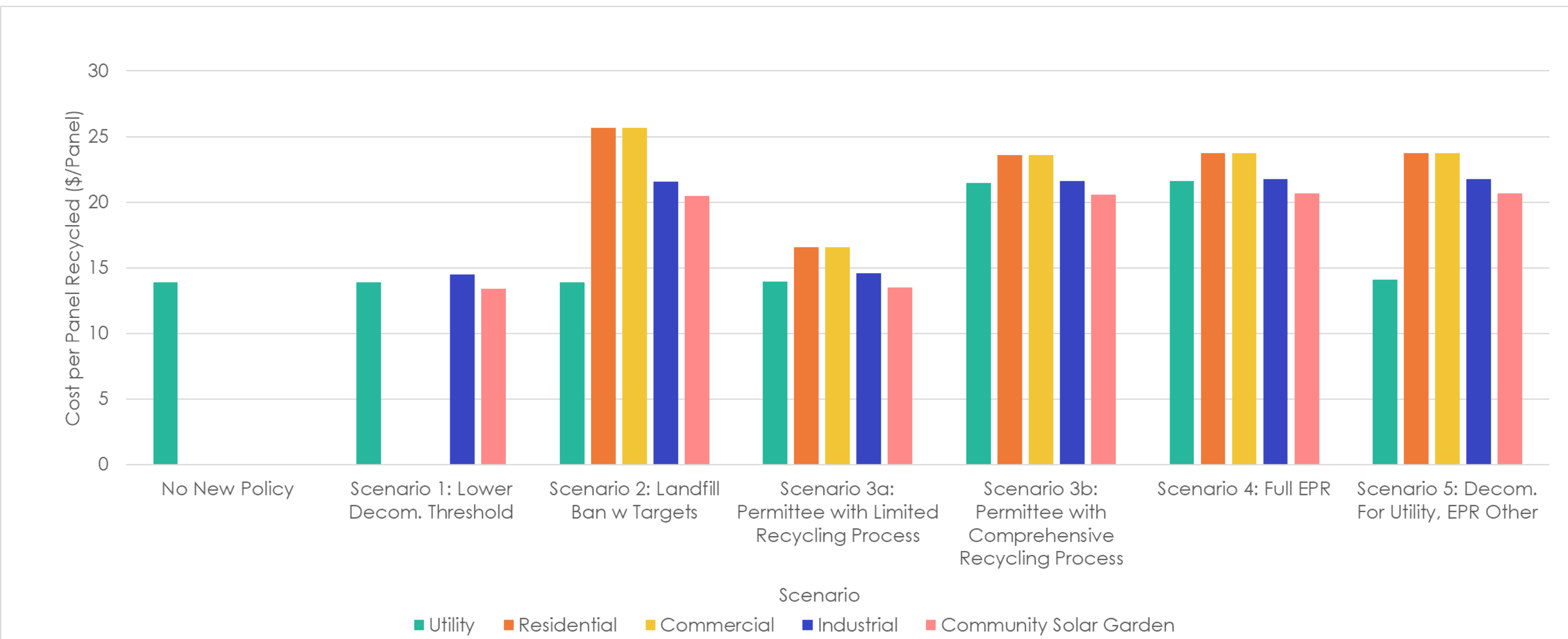
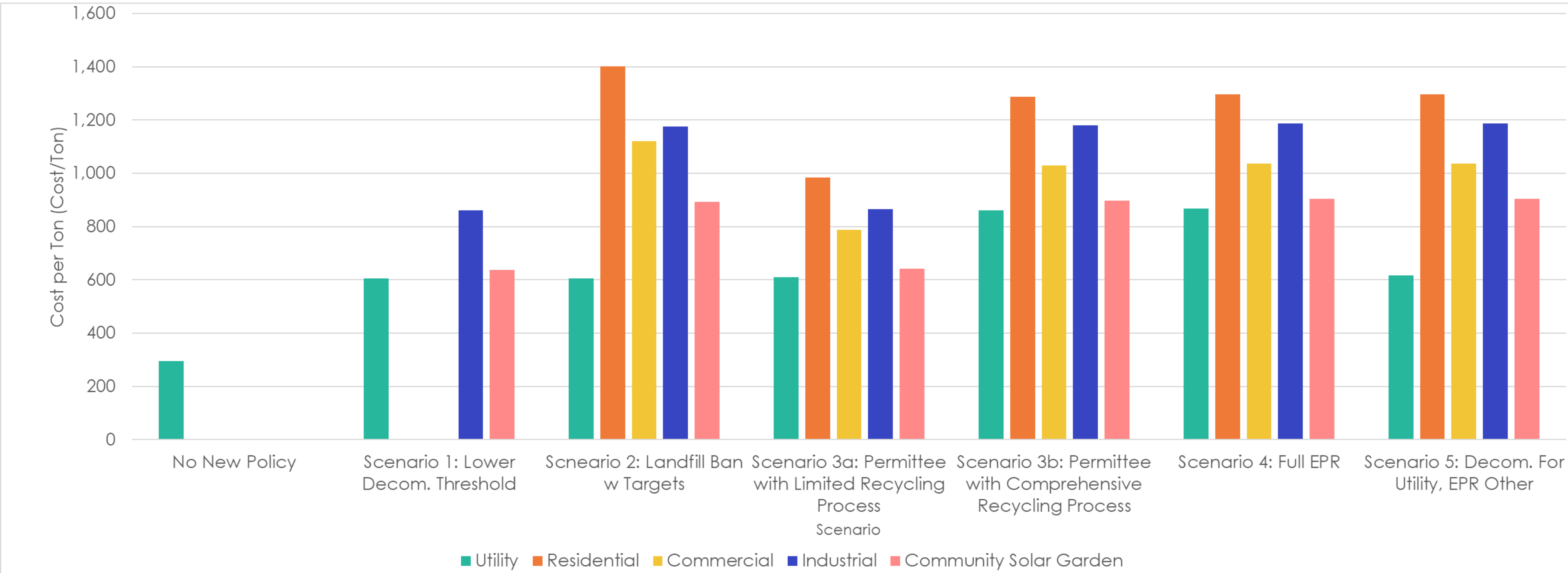


Figure 10 below shows the cost per ton across sectors and scenarios. Cost per ton differences reflect both the processes for each sector and the relative weights of the panels. For example, while residential and commercial panels undergo similar processes, residential panels are assumed to be 10 lbs. lighter than commercial panels. CSG and Utility panels are also heavier than residential as they include a mix of silicon and cadmium based thin film panels.

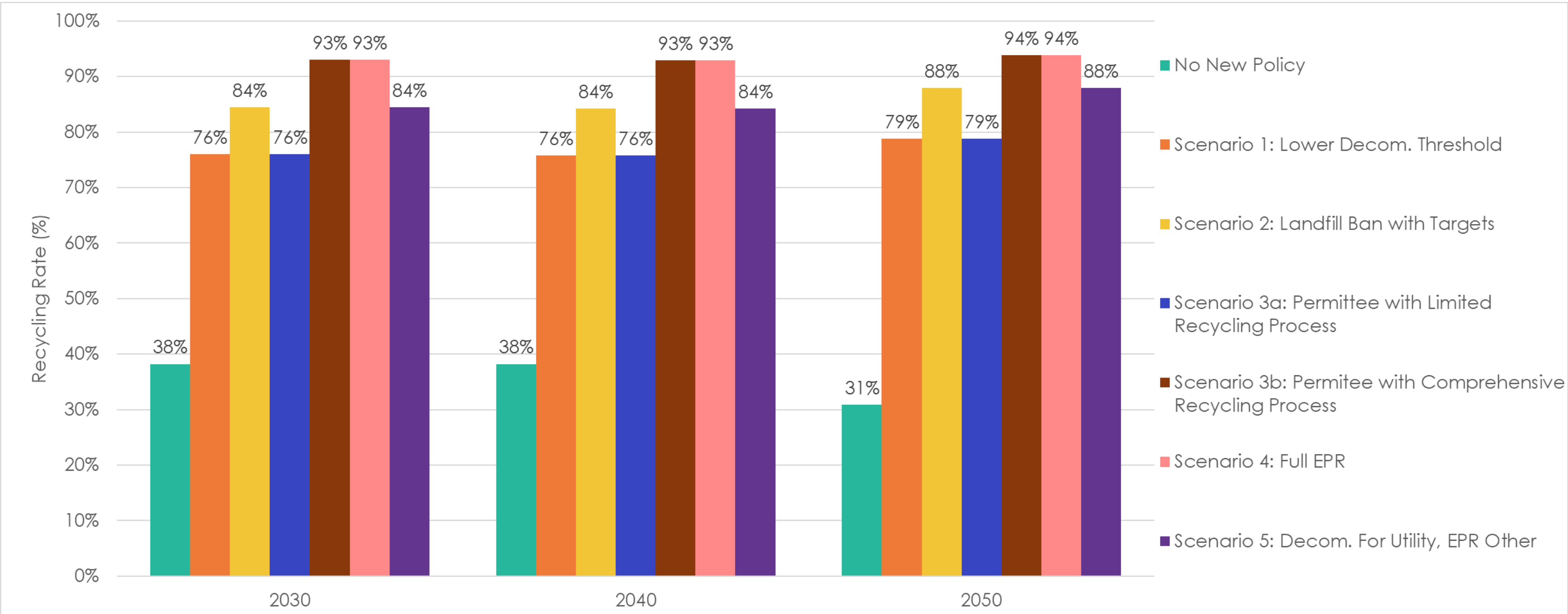
Figure 10: Cost per Ton of Recovering Solar PV Panels in 2050, by Sector



Costs per sector are detailed further in Section 4.1.3. Reuse and Recycling rates refer to the percentage of material components recycled from EOL solar PV panels. Eunomia calculated these rates by weight, dividing the total tons of EOL solar PV panel components recycled by the total tons of EOL solar PV panels in each given year, for each scenario. Each scenario has a lead in time of a few years where recycling yields are lower than steady state when using the comprehensive recycling processes.

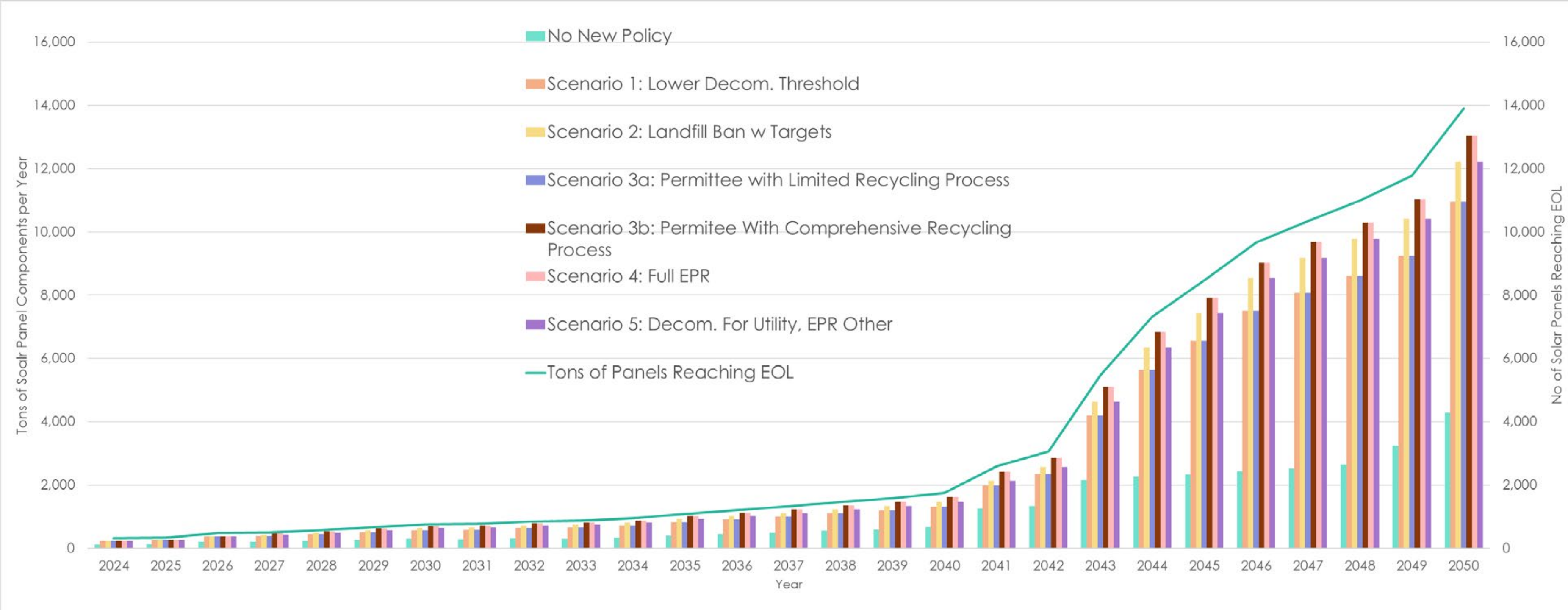
Recycling rates were modeled for 2024 to 2050 and Figure 11 summarizes recycling rates in each scenario in ten-year increments starting in 2030. Every policy scenario has a recycling rate that is at least 37 points higher than in the do-nothing scenario. A lower decommissioning threshold and a permittee funded model with limited recycling each have recycling rates at 76-79% for all years. The landfill ban with recycling targets, permittee pays with comprehensive recycling, full EPR, and decommissioning for utility, EPR for other scenarios have recycling rates between 84% and 93%. Figure 12 shows the total tons of solar PV panel components being recycled against the total tons of EOL solar panels from 2024 to 2050. Recycling rates for each scenario are shown in Figure 11 and detailed in Section 4.2 of this report.

Figure 11. Recycling Rates in 2030, 2040 and 2050 under Different Scenarios



Note that the overall recycling rate does not vary significantly between scenarios with limited recycling and those with comprehensive recycling because the weight percent recovery may only differ by about 10 percent. However that additional 10 percent by weight includes most of the panel material value, which helps offset the higher cost to the permittee for comprehensive recycling. It is difficult to quantify the strategic/national security value or overall environment benefit of recovering and reusing these materials versus extraction and processing of virgin materials.

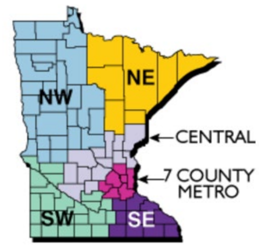
Figure 12. Tons of Solar PV Panel Components being Recycled Vs Tons of EOL Solar PV Panels



System Infrastructure and Technology Needs

Under each of the policy scenarios modeled there is expected to be additional infrastructure and technology needs for Minnesota to properly manage EOL solar PV panels. Eunomia assessed these infrastructure needs and found that additional points of collection for small-scale solar installations and additional solar PV panel recycling locations will be needed.

Figure 13. Minnesota Planning Regions



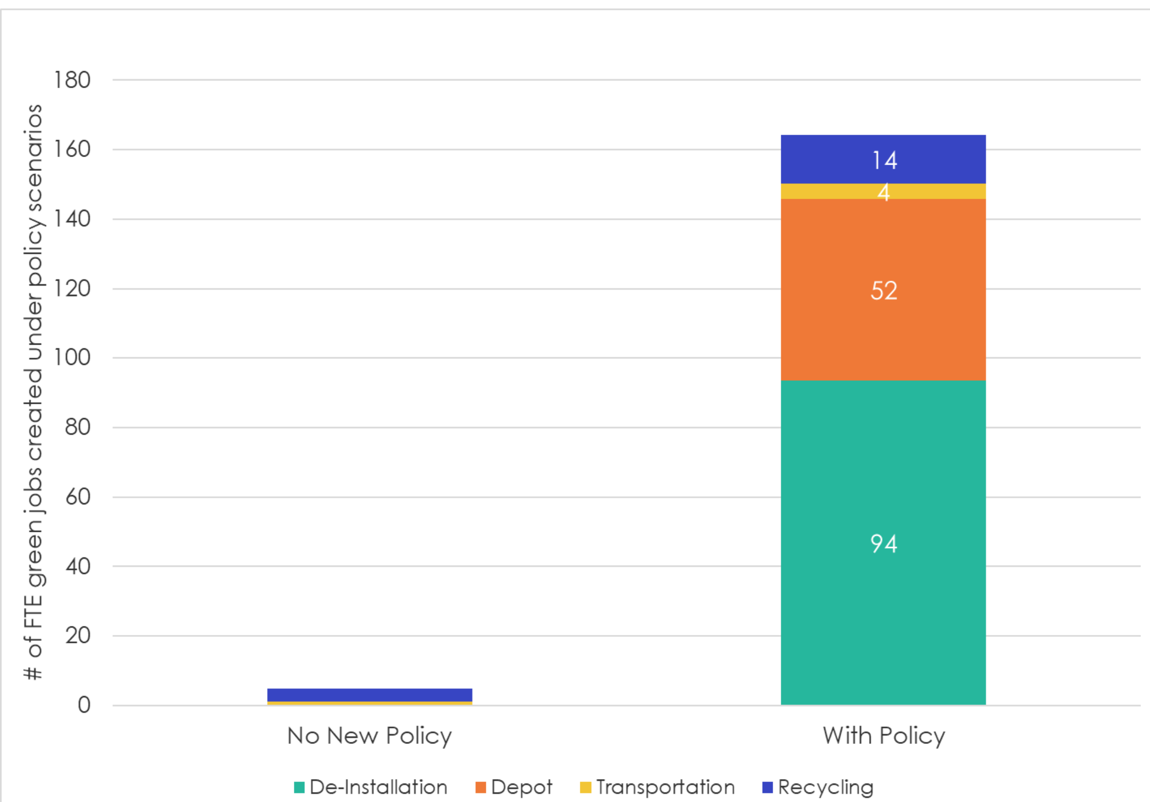
The modeled policy scenarios include one additional point of collection for small-scale solar installations per county, resulting in 83 additional collection points and one small scale recycler per planning region (see Figure 13), resulting in 6 facilities in total. Section 4.3 of this report details the type of collection sites and recycling locations that could be introduced.

Economic Development

Eunomia conducted a bottom-up, activity-based job estimation based on the time and person power it takes at each stage of recycling the panels in order to estimate the total number of jobs required to collect and recycle EOL solar PV panels in 2050. Key assumptions made in this estimation are outlined in Table 46 of this report.

The estimation resulted in a total of 164 direct FTE (Full Time Employee) green jobs being created under the policy scenarios, with only 5 FTE jobs created under the No New Policy Scenario, as shown in Figure 14. The key assumptions of these estimates and detailed results are included in section 4.4 of this report.

Figure 14. Green Jobs in 2050 Under Policy Versus No New Policy



Environmental Justice Impacts

This study included an examination of the potential for each solar EOL policy scenario to address environmental justice (EJ) issues related to solar PV panel end-of-life management, which would augment existing policies that already address these concerns to some extent. As part of PSI's stakeholder consultation process, interviewees were asked about the potential benefits and negative impacts of solar PV panel recycling on Minnesota communities, including environmental justice communities. The five environmental justice considerations that were raised most frequently during interviews were:

- Solar EOL policy should ensure use of responsible end markets,
- Solar EOL policy should ensure the occupational health and safety of solar recycling workers,
- Emissions from transportation should be minimized,
- Communities should be engaged early and often in the siting, permitting, and oversight of solar PV recycling facilities, and
- Materials recovery and recycling should be maximized.

The modeled policy approaches for EOL solar PV, if implemented, would interact with, and/or lay atop existing laws and regulations at the federal, state, and local levels. It is important to note that the policy options under consideration would be established for the State of Minnesota and would not govern what happens on sovereign Tribal lands. A breakdown of how each policy scenario could potentially address EJ concerns is provided below.

No new policy: This scenario does not address responsible markets, occupational health and safety, transportation emissions, and community engagement in solar recycling facility siting and operations.

Scenario 1 - Decommissioning for all grid-tied installations (e.g., <1 MW): This policy will address responsible end markets if the statute requires the use of third-party certified recyclers for all solar PV panels subject to decommissioning. This certification could be modelled on requirements in Minnesota's electronics EPR regulation, Section 115A.1318. For solar installations under the decommissioning threshold (e.g., < 1 MW), this scenario would do no more than current regulations to address responsible markets, occupational health and safety, transportation emissions, or community engagement.

Scenario 2 - Landfill ban with targets: This scenario does not address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement. However, it does prevent environmental contamination of land and water resources.

Scenario 3 - Permittee / Owner Pays: This policy assumes a central body that would have control over program operations. Therefore, the statute could include provisions that address EJ concerns. For example, the policy would address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement if the statute included provisions similar to Minnesota's packaging EPR law. The packaging EPR law requires a living wage for all program workers and third-party certification that materials are sent to a market where materials are handled per Minnesota's waste hierarchy, in a manner that protects the environment, minimizes risks to public health and worker health and safety, complies with all applicable laws, and minimizes adverse impacts to environmental justice areas. Alternatively, this scenario would more narrowly address responsible end markets by adopting provisions similar to Minnesota's e-waste regulation. Additionally, because this scenario assumes EOL funding would be secured at purchase or installation of the panels through a permittee fee, this policy would do more to prevent abandoned and illegally dumped EOL solar PV than no new policy or scenarios 1 and 2.

Scenario 4 - Full EPR: Similar to the permittee scenario, a Full EPR model has a central body – a producer responsibility organization – which is accountable for the program. A Full EPR policy would address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement by including policy provisions similar to Minnesota's packaging EPR law. The packaging law requires a living wage for all program workers and third-party certification that materials are sent to a market where materials are handled per Minnesota's waste hierarchy, in a manner that protects the environment, minimizes risks to public health and worker health and safety, complies with all applicable laws, and minimizes adverse impacts to environmental justice areas. Alternatively, the Full EPR policy would address responsible markets more narrowly by requiring the use of third-party certified recyclers as in Minnesota's electronics EPR law. Additionally, because EOL funding would be secured upon purchase of the panels, this policy would do more to prevent abandoned and illegally dumped EOL solar PV than no new policy or scenarios 1 and 2.

Scenario 5 - Decommissioning for utility, Full EPR otherwise: For the decommissioning portion, the regulation would further address responsible end markets by requiring use of third-party certified recyclers, as in Minnesota's e-waste regulation. It would do no more than current laws and regulations to address occupational health and safety, transportation emissions, and community engagement. The Full EPR portion would address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement by including provisions similar to Minnesota's packaging EPR law, as described in scenarios 3 and 4. Alternatively, the Full EPR policy would address responsible markets more narrowly by requiring the use of third-party certified recyclers as in Minnesota's electronics EPR law. Additionally, because EOL funding would be secured at purchase or installation of the panels, this policy would do more to prevent abandoned and illegally dumped EOL solar PV than no new policy or scenarios 1 and 2.

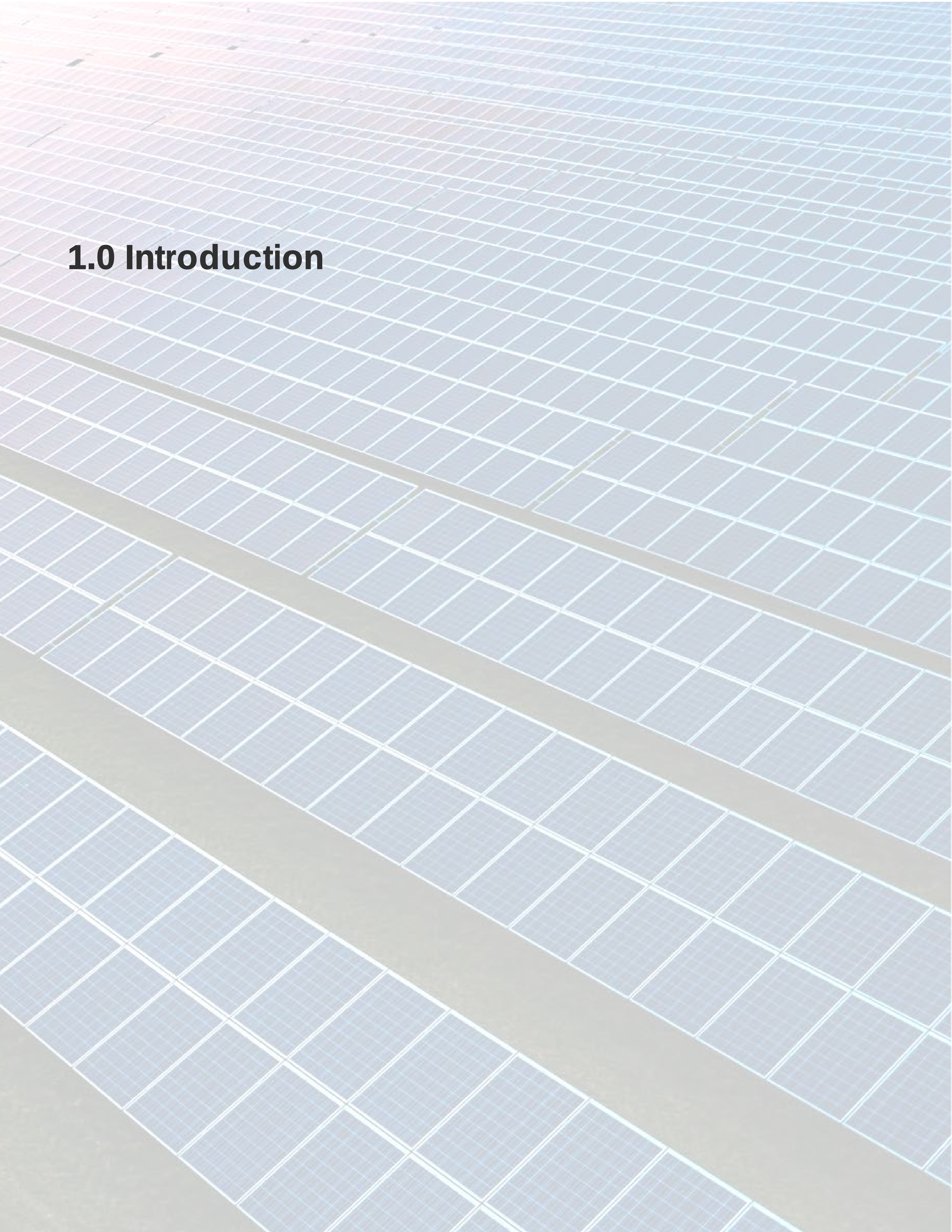
Next Steps

This report's findings on overall costs, per panel costs, recycling rates, infrastructure needs, economic impacts, and environmental justice impacts (detailed in Section 4.0) will be further analyzed by the MPCA and the Policy Working Group (PWG). The MPCA, with the PWG's input, will develop policy recommendations, to help guide the legislative process and support the development of a comprehensive EOL management system for solar PV panels in Minnesota. The MPCA is required to submit the report and accompanying policy recommendations to the relevant legislative committees by January 15, 2025.

Acronyms

Acronym	Definition
CHP	Combined heat and power
CSG	Community Solar Gardens
EIA	U.S. Energy Information Administration
EJ	Environmental Justice
EOL	End-of-Life
EPR	Extended Producer Responsibility
GIS	Geographic Information System
IDP	Integrated Distribution Planning
IPP	Independent Power Producer
IRP	Integrated Resource Plan
HHW	Household Hazardous Waste
MDP	Minnesota Department of Commerce
MnSEIA	Minnesota Solar Energy Industries Association
MPCA	Minnesota Pollution Control Agency
PAT	Project Advisory Team
PFAS	Per-and polyfluoroalkyl substances
POM	Put-on-Market
PS	Product stewardship
PSI	Product Stewardship Institute
PSO	Product Stewardship Organization
PWG	Policy Working Group
PV	Photovoltaic
R&D	Research and development
WtE	Waste-to-Energy

1.0 Introduction



1.1 Purpose

The 2023 legislation in Session Laws Chapter 60, Article 1, Section 2, Subd 7(m), and Article 3, Section 36 enacted a requirement for the Minnesota Pollution Control Agency (MPCA) to commission a study on 'RECYCLING AND REUSING SOLAR PHOTOVOLTAIC MODULES AND INSTALLATION COMPONENTS.' The MPCA secured the services of Eunomia Research and Consulting, Inc. (Eunomia) with support from the Product Stewardship Institute (PSI) to develop a Solar PV Panel Reuse and Recycling Study that includes modeling and input of key stakeholders.

The enabling statute also requires MPCA to convene a Policy Working Group (PWG), with members representing a cross-section of interests, to advise the agency on policy recommendations for system options intended to meet the criteria and analyses outlined in the study legislation. The Solar PV Panel Reuse and Recycling Study will be used by the PWG to advise the MPCA on developing policy recommendations which the MPCA will submit to the Minnesota Legislature by January 15, 2025, for the preferred statewide system for solar equipment end-of-life management.

1.2 Background

MPCA has worked with a broad group of stakeholders since 2019 to identify policy solutions for the end-of-life (EOL) management of solar PV panels. This work included hosting seven technical webinars from June 2019 to December 2020. The stakeholder engagement process included implementing a survey that enabled stakeholders to express their position on various policy options and rank the four overall policy models that were discussed with the stakeholder group. Based on this work, MPCA pursued a product stewardship model for solar PV panel end-of-life management as a legislative proposal in the 2022 legislative session. Subsequently, the proposal was introduced as HF4492/SF4062 during the 2022 Minnesota legislative session to manage solar photovoltaic (PV) modules, installation components, and inverters through an extended producer responsibility (EPR) approach. MPCA made this proposal because it was the model that most closely aligned with stakeholder perspectives, including:

- Coverage of all solar modules in all installations
- Stewardship assessment fee at purchase is visible, fair and equitable to all
- Manufacturer involvement for design and material considerations for recycling, reuse and worker safety
- A single end-of-life program for the entire state, not dependent upon permittee decisions or state or local regulatory authority

Although counties and other local governments supported the proposal introduced in 2022, the solar industry expressed concerns, and the bill failed to pass during the 2022 session. When the EPR bill did not receive a hearing, MPCA proposed a recycling study, but the 2022 Legislature did not act on this proposal either.

In the 2023 legislative session, the governor's legislative package included a proposal for a recycling study and report that would be commissioned by the MPCA. The proposal language was developed with contributions from the Minnesota Solar Energy Industries Association (MnSEIA) and the Department of Commerce (MDC). This study and report would be the basis of recommendations for an end-of-life management program and funding mechanism for solar PV panels. The legislation for the study and appropriation were enacted by the 2023 Legislature. MPCA solicited proposals for the study and selected Eunomia and the Product Stewardship Institute in the Spring of 2024 to perform the study.

Figure 15. Solar PV Panel Policy Process Timeline Prior to 2024 Study

2019 to 2020

MPCA held 7 webinars on solar panel stewardship and end-of-life management to gather stakeholder input on policy design; coalesced around four policy options.

2022

A legislative proposal covering all modules including a stewardship assessment fee on each module was introduced, but did not pass.

2023

The state legislature enacted a requirement for MPCA to conduct a study on solar equipment installation and removal rates and propose EOL management options for a statewide collection, reuse, and recycling system.

2024

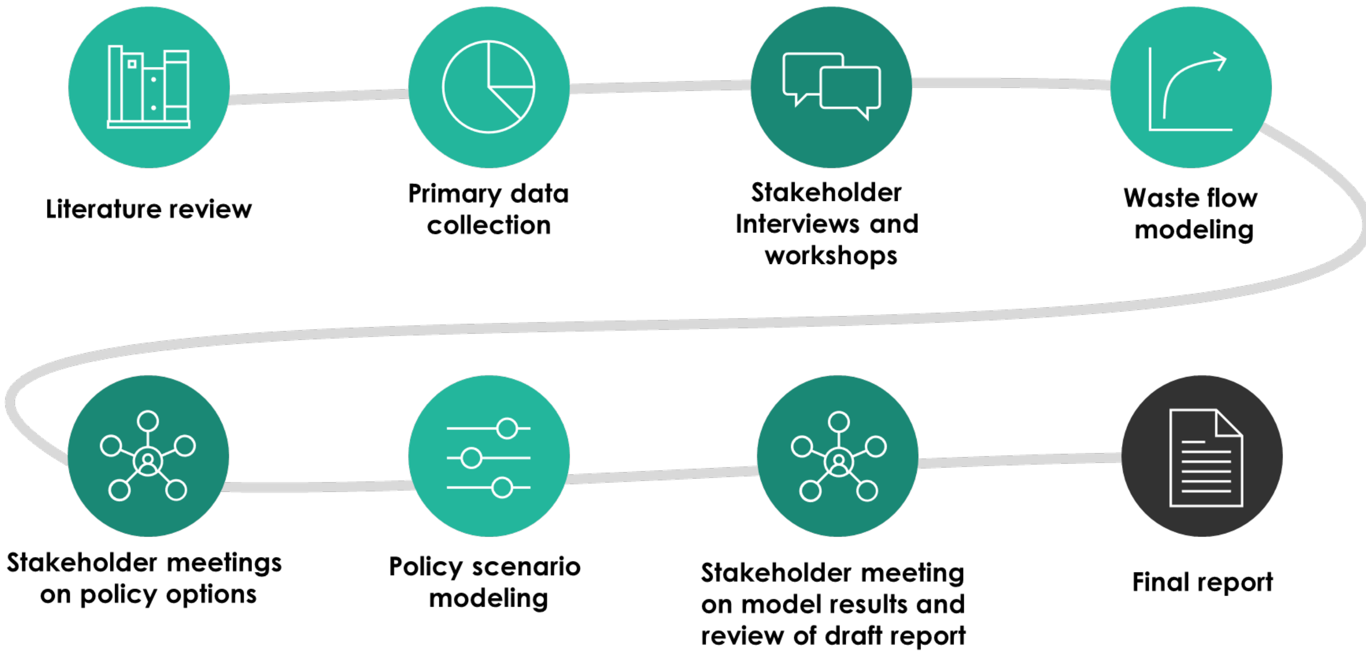
MPCA hired Eunomia and PSI to conduct the study and assess policy scenarios for a statewide reuse and recycling system.

1.3 Study Overview

The project approach, summarized in Figure 16, began with a desktop literature review of the solar PV panel regulatory landscape in the US and internationally. This information helped determine the suite of policies that the project team ultimately recommended for analysis in this study. Simultaneously, the project team collated available solar PV panel waste, economic, and programmatic data on residential, commercial, and utility-scale solar PV panel installations. This data review, along with 1:1 interviews with stakeholders and stakeholder workshops to review proposed policy options, fed into the waste flow modeling and scenario modeling exercises. The project team then presented model results and shared an initial draft report with the PWG, and integrated feedback into this final report deliverable.

It is important to note that EOL solar PV panel stakeholders who are members of the Policy Working Group (PWG) will have additional opportunities to provide input as the MPCA builds upon the findings in this report to develop the policy recommendations that will ultimately be submitted to the Minnesota Legislature in 2025.

Figure 16. Project Approach



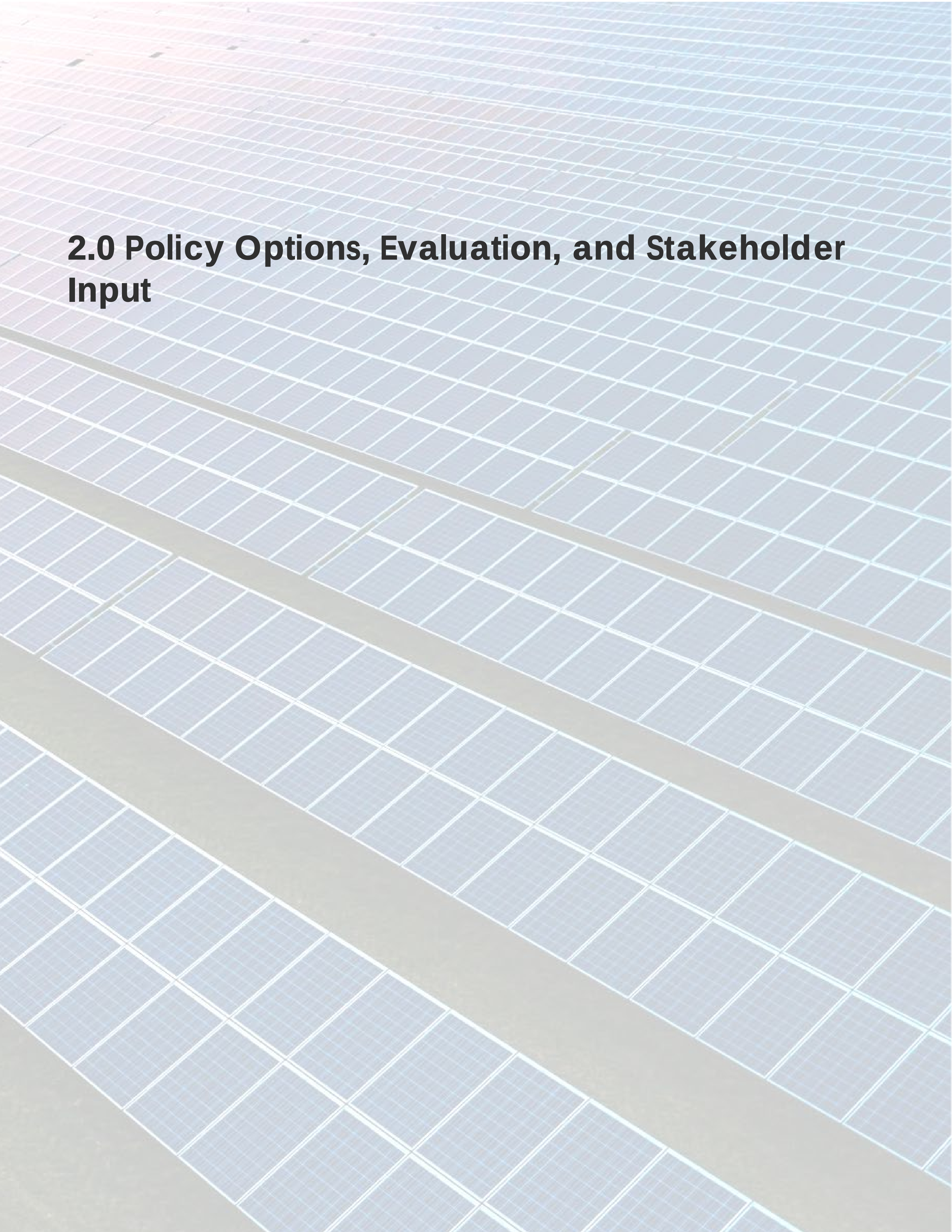
This report is broken down into three main sections:

- **Policy Options, Evaluation, and Stakeholder Input - Section 2.0** provides an overview of the project team's process to determine what scenarios to model. After completing a full review of MPCA's previous work to identify policy solutions for the end-of-life (EOL) management of solar PV panels, the project team performed a policy landscape review and held interviews and workshops with stakeholders along the solar PV panel value chain to determine a list of policies to evaluate. This section outlines the criteria that each policy was evaluated against and summarizes findings from the stakeholder input that shaped the assumptions used in the model and policy scenario design.

- **Modeling Approach - Section 3.0** outlines the methodology, data sources, and assumptions used to estimate current and projected solar PV panel installation and waste generation and the results from that modeling exercise. The project team then modeled five different policy scenarios (in addition to a baseline, no new policy scenario). This section provides an overview of each scenario, the key modeling assumptions behind each, and the data sources used to estimate costs along the value chain including the deinstallation, collection, consolidation, transportation, and dismantling of solar PV panels, as well as program management costs.

- **Results and Key Findings - Section 4.0** presents the statewide results across each policy scenario modeled, including the total and per panel costs and recycling rates estimated for each scenario. The section also includes expected additional infrastructure needs for Minnesota to properly manage end of life solar PV panels and the number of jobs required to collect and recycle EOL solar PV panels in the future. Lastly, there is an analysis of the potential for each policy option to address environmental justice issues related to solar PV panel end-of-life management.

2.0 Policy Options, Evaluation, and Stakeholder Input



To develop the policy scenarios to model, the project team first identified a shortlist of potential policy options to address solar PV panels at EOL, then developed evaluation criteria to determine which policy options would be most relevant to model in this study.

The first step in determining what scenarios to model built upon the work MPCA had already performed to narrow down policy options. Since 2019, MPCA has worked with a broad group of stakeholders (e.g., hosting workshops and implementing surveys) to identify policy solutions for the EOL management of solar PV panels. From this process, MPCA established the following goals for a solar PV panel EOL policy in Minnesota, as shown in Figure 17.

Figure 17. MPCA's Solar PV Panel EOL Management Policy Goals

1. Create a statewide program and sustainable funding mechanism that does not require a fee at the time of disposal/recycling.
2. Require recycling and reuse of end-of-life solar panels and include a disposal ban.
3. Encourage sustainable materials and design of solar panels by manufacturers.
4. Internalize costs to the project or developer.
5. Does not disadvantage anyone in the Minnesota solar panel market regarding costs.
6. Achieve consistency and predictability.
7. Applies to all solar panels installed in Minnesota, from residential-scale to utility-scale projects.
8. Reduce national security concerns associated with dependence on other countries for scarce critical materials and finished products.
9. Sustainable end-of-life program funding source(s) associated with solar energy activities.

Considering these goals, MPCA and stakeholder participants had identified four potential policy solutions that would include a reuse and recycling requirement:

(1) extending decommissioning plan requirements for utility and commercial PV facilities under 50MW,
(2) a product stewardship program,
(3) a ratepayer funded program, and
(4) a permittee funded program.

After completing a full review of MPCA's previous work to determine policy options, a literature review, interviews with stakeholders along the solar PV panel value chain, and workshops with the Project Advisory Team (PAT), the project team added two additional policies for consideration in this study:

(5) landfill bans, and
(6) targets for collection, reuse, and recycling.

Section 2.2 provides detailed descriptions of each of the six potential policy solutions identified. The project team also developed evaluation criteria to determine which policy options would be most relevant to model as part of this study. Section 2.1 provides an overview of the criteria each policy was evaluated against and Section 2.2 describes and evaluates each policy against these criteria. Section 2.3 provides an overview of findings from value chain stakeholders on the various policy options.

2.1 Criteria for Policy Evaluation

Before modeling policy scenarios, Eunomia conducted a thorough evaluation of each policy's effectiveness in achieving the goals set by the MPCA, as outlined in Figure 17. This process began with an internal workshop where the project team reviewed MPCA's policy objectives and aligned them with Eunomia's and PSI's expertise on best practices for managing EOL products. The criteria, listed in Figure 18, were developed with the overarching goal of creating a robust market for the reuse, recycling, and safe disposal of PV panels. Following this workshop, the team conducted a comprehensive review of existing EOL policies and regulations for solar PV panels in both the U.S. and internationally.

Figure 18. Best Practice Policy Evaluation Criteria

Covered PVs & Entities

The policy covers all PV types and includes residential, commercial, and utility installations, providing all stakeholders with equitable access to the program.

Internalized Cost

The policy includes a funding mechanism to cover the cost of managing PV panels at their end-of-life. There are three primary sources of funding: taxpayers/ratepayers, permittees/owners, and the solar industry.

- **Taxpayer/Ratepayer**: When the cost of EOL management is spread across the public, it is externalized. This means the individuals and businesses who did not directly create the panels or benefit from their energy production are forced to bear the cost. This could lead to negative environmental impacts because there is little incentive for solar PV panel owners or manufacturers to reduce the waste associated with their products.

- **Permittee/Owner**: Internalizing the cost to the PV owners or permittees ensures that those who financially benefit from using the solar PV panels take responsibility for their environmental impact. This creates an incentive for owners to properly dispose of or recycle the panels when they reach the end of their life.

- **Solar Industry**: Internalizing the cost to those that place Solar PV panels on the market and benefit financially from their production or sale most closely aligns with the Coase theorem. Internalizing these costs may also improve product design for reuse, recycling, and safe disposal. This practice creates an incentive to minimize negative externalities and leads to more sustainable practices across the product lifecycle.

The best practice is to assign the cost of managing the end-of-life of solar PV panels to the party responsible for bringing the product to market.[a] This practice minimizes downstream cost increases that would disproportionately affect low-income consumers, since the cost is spread over so many units. This practice also

[a] The Coase theorem offers insights into how external costs, such as waste and pollution, can be addressed efficiently. In the case of solar PV panels, the externality is the environmental cost of managing the panels when they reach the end of their useful life. Coase's theorem suggests that instead of externalizing costs on society at large (through taxpayers or ratepayers), it should be internalized by the parties directly involved in creating and benefiting from the product.

eliminates a recycling fee at the point of disposal, which is a cost barrier known to incentivize illegal disposal and dumping.

Organized Collection

The policy requires or allocates funding to establish collection points that are equitably accessible to all, such as take-back systems, retail returns, and distributor returns to promote PV reuse or recycling. The policy requires collection/take back when installing new Solar PV panels, which maximizes convenience and efficiency. Organized collection enables transparent reporting about where panels are sent and how they are managed, ensuring protective environmental, health, and safety practices along the end-of-life value chain.

Investment in Recycling and Reuse Capacity

The policy's funding mechanism includes investment in infrastructure and R&D. Investment is crucial for scaling up infrastructure to handle the increasing volume of solar PV panels reaching their end-of-life. R&D is essential for improving material recovery, enhancing the cost-effectiveness of recycling, and advancing the refurbishment of panels for reuse.

Performance Targets

The policy establishes measurable performance metrics for collection, reuse, and recycling efforts. Best practice targets should address:

- Collection methodology that is based on expected EOL volumes and set achievable targets.
- Collection convenience metrics that ensure equitable access to all installation types.
- Reuse targets that consider the failure rate and degradation rate of solar PV panels.
- Recycling targets that incorporate requirements to recover valuable materials that are present in solar PV panels in small quantities and may be disposed. Consider value-based metrics to ensure critical materials are not overlooked in favor of heavier, lower-value components like glass and aluminum which are easier to prioritize using weight-based recycling targets.
- Data collection to monitor progress toward meeting collection and recycling targets, convenience, and responsible markets (e.g., protective environmental, health, and safety along the value chain).
- Enforcement mechanisms to deter non-compliance.

Design for Reuse and Recycling

The policy encourages design to facilitate disassembly for reuse or recycling of solar PV panels and avoid hazardous substances.

2.2 Policy Options and Evaluation

Based on the outlined criteria in Figure 1, the team reviewed and rated the policies as described in Table 5. It is important to note that each policy was evaluated individually. During the development of policy scenarios, the team also considered how certain policies could be combined to optimize alignment with the best practice criteria.

Table 5. Policy Evaluation Rubric

The policy achieves best practice for this criterion.	The policy can integrate this through policy design or implementation to meet the best practice.	The policy does not meet best practice for this criterion.

Setting mandatory collection, reuse, and recycling targets

Establishing mandatory collection, reuse, and recycling targets is a policy mechanism that sets minimum performance standards to establish circularity. To ensure success, the targets must be grounded in the current capacity of collection and recycling infrastructure, with achievable milestones. Staggered targets that ramp up over time can foster continuous improvement. Clear methodologies for measurement, coupled with strong monitoring and enforcement mechanisms, is essential to drive compliance.

Targets focus on the downstream management of solar PV panels and apply to owners, permittees, or any parties responsible for deinstalling solar PV panels. These entities are required to ensure that decommissioned panels are collected and delivered to a transfer station, certifier for reuse, or recycler.

Achieving targets requires investment in infrastructure, efficient recycling and remanufacturing processes, and the development of stable end markets for recovered materials. While targets may incentivize such investment, they do not provide a direct funding mechanism. Therefore, while targets can function as standalone measures, they are most effective when integrated with other policies that facilitate investments in the EOL management of PV panels and modules.

Targets should be regularly reviewed and adjusted based on market conditions and technological advancements. If the market for solar PV panel collection, reuse, and recycling is evolving quickly, targets can be ramped up to encourage continuous improvement and drive further innovation. However, if the market is slow to develop or infrastructure is lagging, it may be necessary to reassess the targets and provide additional support or flexibility to ensure they remain achievable.

Set Minimum Collection Targets

Minimum collection targets establish a goal for the percentage of solar PV panels that must be recovered for reuse, recycling, or safe disposal. Collection targets should be based on a clear methodology that estimates the actual tonnage of solar PV panels coming offline to ensure they are achievable.

Set Minimum Reuse Targets

Panels retain some functional capability after use, with degradation rates under 1% annually[4]. Repaired PV panels can be sold as used panels at a reduced price. Challenges in developing a reuse market for solar PV panels include financial feasibility, regulatory barriers, operational concerns, and consumer acceptance due to quality uncertainties. Establishing standardized certification for second-hand panels within solar PV panel EOL legislation to support safety, performance, and quality standards could mitigate these challenges. More details on the barriers to developing repair and reuse markets for EOL solar PV panels can be found in Section 2.2.1 Policy Challenges.

Set Minimum Recycling Targets

Minimum recycling targets establish the percentage of materials from solar PV panels that must be recycled. Calculation methodologies for recycling rates often use weight-based metrics. Solar PV panels primarily consist of glass, aluminum frames, and encapsulants, accounting for around 90% or more of their weight.[5] The focus on weight-based metrics poses a potential problem as recycling efforts may concentrate on these heavy, low-value materials.

Prioritizing value-based metrics instead of weight-based metrics ensures that critical materials like silver, copper, and silicon, despite their low weight, are effectively recovered. These valuable components may be about 5% of a solar PV panel's weight but represent over 50% of the panel's economic value. Recycling rate methodologies need to consider how to incorporate value-based metrics to ensure that valuable materials are not overlooked in the recycling process. Additionally, any remaining toxic materials must be disposed of responsibly.

Figure 19. Evaluation of Targets against Best Practice Criteria

Targets cover all solar PV panels.

Targets do not provide a funding mechanism to cover the costs of managing EOL solar PV panels or compliance enforcement. Compliance falls on owners and permittees, who will, in most cases, internalize the costs to ensure the solar PV panels they manage are collected for reuse and recycling. These costs may be shared with installers and developers involved in the installation and decommissioning of solar PV panels. However, the lack of funding may contribute to illegal disposal or dumping.

Although targets set a minimum collection threshold, they do not provide funding for collection infrastructure. Funding for this infrastructure may fall on multiple stakeholders, including local or state governments, waste haulers, installers, owners, and permittees. Ensuring accessibility and convenience for solar PV panel owners is crucial to facilitate effective collection and promote higher participation in recycling and reuse efforts. While targets provide an incentive to establish convenience, insufficient funding could result in insufficient infrastructure and inequitable access to reuse and recycling.

Targets require specific end-of-life treatments but do not provide a funding mechanism to expand collection, treatment, recycling, and reuse efforts. However, they may spur voluntary R&D and investments aimed at meeting recycling and reuse targets. For instance, a target that mandates the recovery of valuable materials like silver and copper could encourage investment in recycling processes and technologies that improve material recovery.

This policy sets targets for collection, reuse, and recycling.

Targets deal with downstream management and do not incentivize manufacturers to design for reuse, recycling, or the minimization of hazardous materials.

State utility scale decommissioning programs

Decommissioning policies for solar energy facilities require developers to provide an upfront plan for dismantling and removing solar installations, ancillary equipment, related structures, and restoration of the land to its original state. Developers must submit detailed decommissioning plans, which outline the processes for site reclamation, infrastructure removal, and cost estimates; these plans typically require periodic updates following initial approval. To cover the costs associated with decommissioning, owners must provide financial assurance, such as bonds or letters of credit, before construction or operation begins. These financial assurances help mitigate the risk of orphaned panels in the event the developer or owner is out of business at the panels' end of life. Cost coverage requirements, which vary by state, generally include expenses for infrastructure removal, site restoration, and administrative costs, with some states accounting for the salvage value of PV panels and other system components.

Originally created for fossil fuel technologies, decommissioning policies have been adapted for renewable energy but face several challenges. They focus primarily on removal and site restoration costs and do not account for the cost of managing panels once they are removed. Additionally, these policies do not address the creation of responsible supply chain management. While dismantlers or scrappers are typically named in decommissioning plans, no further information is reported. Decommissioning policies also usually apply only to larger solar installation, like industrial or large commercial arrays. There is also the challenge of handling individual panels that break or need replacement before the entire installation is decommissioned.

Additionally, compliance requirements, such as submitting decommissioning plans and securing financial assurances prior to each project, may delay timelines and increase capital costs. However, drawing from established programs like the MPCA's Financial Assurance program for landfills could provide a valuable framework for solar decommissioning. The MPCA program is well-regarded for accounting for the risk profiles of different entities, thereby tailoring financial assurance requirements based on the entity's ability to meet its decommissioning obligations.

Figure 20. Evaluation of State Utility Scale Decommissioning Programs Against Best Practice Criteria

This policy excludes residential and some commercial PV installations.

Decommissioning plans typically focus funding solely on the removal of solar PV panels. However, this policy could be adapted to expand funding to cover the full cost of EOL management. This approach would internalize costs for owners and permittees, ensuring that those who benefit from the electricity generated by solar PV panels also bear the responsibility for their proper disposal and management at the end of their life cycle.

Decommissioning plans provide for the removal of solar PV panels at EOL.

Decommissioning plans typically only fund removal of solar PV panels. This policy could be adapted to include investments in infrastructure and R&D to facilitate reuse and recycling.

Decommissioning plans primarily focus on removal and site restoration costs, often overlooking the management of solar PV panels after removal. This policy could be adapted to incorporate minimum targets for reuse and recycling.

Decommissioning plans deal with downstream management and do not encourage designs that facilitate disassembly for reuse and recycling of solar PV panels or minimization of hazardous substances.

Landfill bans on PV panels

Landfill bans are a policy tool designed to keep recyclable materials out of landfills and encourage the development of alternative EOL options. A landfill ban requires generators to divert PV modules and components from landfills, directing them towards higher-priority waste management pathways such as reuse and recycling. To support this shift, landfill bans can be combined with a surcharge on tipping fees, which raises funds from disposal activities to invest in infrastructure, research and development, education, and enforcement efforts to enhance reuse and recycling. These surcharges can be used to invest in the technology and equipment needed to efficiently dismantle, sort, and recycle the various components of solar PV panels.

However, landfill bans have only proven successful in the EU when combined with other instruments, such as EPR and pre-sort requirements. Without affordable alternatives, landfill bans may increase the difficulty and costs associated with monitoring and combating illegal dumping. Additionally, imposing a surcharge on tipping fees can be politically challenging and may lead to the export of waste to states without bans or with lower fees.

Figure 21. Evaluation of Landfill Bans against Best Practice Criteria

Landfill bans cover all PV panels.

Landfill bans have no funding mechanism whereas surcharges place the financial burden on haulers, who likely pass them on to owners and permittees.

Landfill bans do not require or fund collection systems. Nonetheless, stakeholders in the value chain will likely create and fund collection systems to provide an alternative end market for solar PV panels that cannot be sent to landfills. However, without system requirements or oversight, these market-driven collection systems may not provide equitable access and convenience to all installation types.

Landfill bans do not have a funding mechanism. For landfill bans with surcharges, a part of the funds can be allocated to investments and R&D.

Landfill bans can be combined with collection, reuse, and recycling targets.

Landfill bans deal with downstream management and do not encourage designs that facilitate disassembly for reuse and recycling of solar PV panels or minimization of hazardous substances.

Permittee-funded statewide model

Under a permittee-funded model, owners and permittees of PV facilities are required to finance a statewide program for EOL management. Under current Minnesota regulations, a permittee is defined as any individual or entity that applies to a local government unit or the Department of Commerce for a permit to build and operate a commercial electrical generating facility. Permits for facilities with capacities over 50 MW are submitted to the Department of Commerce, while applications for smaller facilities, between 40 kW and the thresholds for Commerce applications (5 MW for wind and 50 MW for other technologies), are made to local government units, typically counties.

Under this policy, individuals and entities operating solar installations greater than 40 kW would be required to pay a fee for the EOL management of PV systems. If policymakers aim to include smaller installations in the funding model, the legislation has to redefine the term "permittee" to cover installations with capacity under 40kW.

Permittees could be required to pay fees at various points, through a fee applied to each panel at the point of purchase, a dedicated sales tax, a fee based on the electricity generated by the panels, or a levy calculated based on the number of panels installed.

Depending on the funding model, fees could be collected by retailers, importers, utilities, or a government department, such as the Department of Revenue, and then remitted to a central organization responsible for EOL management. This organization would be tasked with handling all aspects of EOL management such as ensuring the recycling of panels, inverters, and other components to a defined standard, managing warranties, and addressing any storm or physical damage to PV systems.

Figure 22. Evaluation of Permittee-Funded Statewide Model against Best Practice Criteria

Fees can go towards funding EOL for all solar PV panels in Minnesota or focus on large generators, such as commercial and utility scale installations > 40 kw. Installations under 40 kw would be omitted without changes to permit requirements.

Costs are internalized by permittees.

Permittee fees fund collection systems.

This policy’s funding mechanism can include investments in reuse and recycling infrastructure as well as R&D.

Permittee fees can be combined with minimum collection, reuse, and recycling targets.

Permittees likely have limited influence over producers and manufacturers, making it unlikely that a permittee-funded model would encourage design improvements for reuse or recycling of solar PV panels or the avoidance of hazardous substances.

Ratepayer-funded statewide model

A state electrical customer or ratepayer-funded program would finance EOL management for solar PV panels through a fee on utility bills. This fee could be based on kilowatt-hour consumption, a flat monthly rate, or a percentage of the total bill. The fee would not necessarily be tied to an individual ratepayer's use of solar power but would likely be calculated based on a statewide average.

The collected fees would be paid to the utility and then remitted to a central organization responsible for overseeing the collection and recycling of solar PV panels, inverters, and other components. A ratepayer funded program would cover all commercial and residential installations, including panels already installed. This approach is comparable to other fees already included on Minnesota utility bills, such as federal excise taxes on landline telephone services used to support federal telecommunications programs.

Figure 23. Evaluation of Ratepayer-Funded Statewide Model against Best Practice Criteria

A ratepayer-funded program would cover all solar PV panels.

This policy externalizes costs to ratepayers, meaning that even those who do not directly benefit financially from electricity generated by solar PV panels would still be required to pay fees for managing EOL solar PV panels. The policy could further specify that costs should be limited to co-generators, a class of ratepayers.

Ratepayer fees can fund collection system.

Fees go towards EOL, including reuse and recycling. Requirements to invest in collection, recycling capacity, or reuse would have to be specified in regulation.

This policy can be combined with minimum collection, reuse, and recycling targets.

A ratepayer-funded policy focused on financing EOL PV management emphasizes downstream efforts and does not promote designs that facilitate disassembly for reuse and recycling of solar PV panels or the reduction of hazardous substances.

Extended producer responsibility / product stewardship program

Extended Producer Responsibility (EPR) and Product Stewardship (PS) programs exist on a spectrum, both aiming to improve the end-of-life management of products by increasing collection and recycling rates. However, they vary in the degree of responsibility placed on manufacturers and the legal framework that governs them:

- Product stewardship (PS) is the act of minimizing the health, safety, environmental, and social impacts of a product and its packaging throughout all lifecycle stages, while also maximizing economic benefits. The manufacturer or producer of the product has the greatest ability to minimize adverse impacts, but other stakeholders, such as suppliers, retailers, and consumers, also play a role. Stewardship can be either voluntary or required by law.[6]

- Extended producer responsibility (EPR) is a mandatory type of product stewardship. It includes, at a minimum, the requirement that the manufacturer's responsibility for its product extends to post-consumer management of that product and its packaging. There are two related features of EPR policy:

  (1) shifting financial and management responsibility, with government oversight, upstream to the manufacturer and away from the public sector; and

  (2) providing incentives to manufacturers to incorporate environmental considerations into the design of their products and packaging. EPR levels the playing field among competitors and incentivizes environmentally conscious design.[7]

Under EPR, producers and manufacturers are required to form a producer organization responsible for developing and submitting a plan. This plan would outline how they intend to implement the program, including reporting the number of PV panels and components placed on the market, identifying existing collection and recycling systems, calculating fees, and anticipating necessary investments in infrastructure to handle the increasing volume of solar PV panels coming offline.

Figure 24. Evaluation of Extended Producer Responsibility and Product Stewardship against Best Practice Criteria

EPR and PS programs cover all solar PV panels.

Typically, these policies place the financial burden on producers of solar PV panels. However, the majority of solar PV panels are produced overseas and imported into the US. Given the challenge of imposing fees on foreign producers, it may be more feasible to place the fees on entities such as importers, permittees, and owners.

Requires collection and investments in collection systems.

Provides for EOL cost coverage and incorporate investment in infrastructure to improve collection, reuse, and recycling.

This policy can be combined with collection, reuse, and recycling targets.

Fees can incorporate eco-modulation to incentivize design for reuse and recycling, use of recycled content, and minimization of hazardous materials.

2.2.1 Policy Challenges

Challenges to consider with policies aimed at improving the reuse and recycling of solar PV panels include difficulty applying the producer pays principle, higher recycling costs compared to disposal, no industry-wide panel reuse testing and certification program, underdeveloped repair and reuse markets, and differing policies across states, all of which may hinder effective policy implementation. These challenges are not unique to a single policy mechanism, but rather should be considered for any proposed policy to address solar PV panels at EOL.

Imported solar PV panels may be harder to regulate

In 2022, around 88% of solar PV panels installed to the U.S. were imported, mainly from Asia.[8] Imposing fees or holding foreign manufacturers accountable for end-of-life management within the U.S. may present challenges. One potential solution is to mandate that all producers register before selling or importing solar PV panels into Minnesota, with non-compliant producers prohibited from accessing the market. Another approach is to place the financial or operational responsibility for end-of-life management on domestic U.S. stakeholders further down the value chain, such as importers, resellers, installers, or permittees.

To alleviate cost pressures on the industry, the state could incentivize responsible practices by providing support to developers and permittees who voluntarily implement initiatives beyond compliance, such as take-back programs, eco-friendly designs, and partnerships with recyclers to ensure sustainable end-of-life management of PV systems. Additionally, the state could offer grants to support investments in PV recycling and reuse infrastructure. This would allow a gradual increase in funding to prepare for the anticipated surge of EOL solar PV panels in the 2030s. Spreading investments over time would be more cost-effective than a last-minute scramble to manage the large volume of panels coming offline simultaneously.

Low cost disposal options undercut reuse and recycling due to their higher cost, in the absence of a mandate

The cost of disposing solar PV panels in the U.S. is currently cheaper than reuse and recycling.[9] The Department of Energy estimates the cost to recycle a PV module ranges from $15 to $45 per module, while landfill fees are significantly lower, at just $1 to $5 per module.[10] Policy and regulation can address this by either increasing the cost of disposing solar PV panels or investing in recycling infrastructure and end markets to make reuse and recycling more economically viable.

Criticisms of policy interventions aimed at increasing reuse and recycling of solar PV panels include the risk that such measures may raise the cost or be perceived as raising the cost of solar PV panels and solar installation projects. At a time when jurisdictions are seeking to expand solar energy to meet decarbonization goals, raising costs of solar PV panels could undermine these efforts. To mitigate this challenge, it is critical to anticipate end-of-life costs and gradually invest in the necessary collection, recycling, and reuse infrastructure. By spreading these investments over time, the industry can absorb costs without causing a market shock. Such a phased approach would lower the cost per panel and help maintain the competitiveness of solar energy. Policymakers must carefully craft EOL management policies for solar PV panels that minimize disruptions to the broader renewable energy market while incentivizing reuse and recycling to be economically competitive with disposal.[11]

Developing repair and reuse markets for EOL solar PV panels

There are multiple challenges in establishing repair and reuse economy for solar PV panels, including regulation, low demand, and market constraints.[12]

Regulations at the state and local level vary and may be unclear about how they apply to repaired or reused PV equipment. In many U.S. states, interconnection, fire, building, and electrical regulations may prohibit the reuse of PV modules.[13]

Interconnection regulations determine how solar PV panels connect to the electric grid and set requirements and procedures that ensure the design and quality of PV electrical equipment meet specific standards. Generally, these regulations fall under the authority of state public utility commissions. However, in areas served by municipal utilities, local governments can also influence interconnection rules. Many jurisdictions in the United States refer to established industry standards, such as those set by the Institute of Electrical and Electronics Engineers (IEEE) and Underwriters Laboratories (UL).[14] Interconnection regulations often prohibit the reuse of older PV modules and balance of system (BOS) equipment that do not comply with these standards. If equipment fails to meet the specifications, it may not be allowed to connect to the utility's distribution system. This situation can effectively limit the ability to reuse older PV equipment in new installations, especially in jurisdictions that have strictly implemented these standards.

Fire and building regulations aim to reduce the risk of fire and minimize potential fire damage to buildings. US states have implemented the International Building Code (IBC) in various forms, outlining safe construction practices. A key component of fire and building regulations involves fire classifications for roofing materials and the PV systems mounted on them. Roof-mounted PV systems must comply with certain fire classification ratings, typically designated as Class A, B, or C, based on their flammability characteristics.[15] Fire safety codes may require that the fire classification of an entire PV system, including modules and mounting, match or exceed the fire rating of the roof coverings[16]. If a reused PV system's rating is lower, it will not be allowed. In high wildfire risk areas, local regulations often mandate Class A fire ratings for roof coverings, which prevents the reuse of older PV equipment that only meets Class B or C standards.

Electrical regulations set installation requirements for electrical equipment, including solar PV panels for grid-tied and off-grid applications. These requirements include certain safety features such as rapid shutdown devices which are essential for protecting installers and first responders from potential electrical hazards during emergencies.[17] PV systems that were installed before the implementation of updated rapid shutdown provisions may not meet modern safety standards and could be prohibited from use in new installations.

These regulations may impede PV reuse, low demand and a lack of consumer confidence in used or refurbished products may further discourage investment in PV repair and reuse.[18] This could be mitigated by the adoption of third-party verification and certification. Although some independent businesses conduct tests to ensure the safety, quality, and performance of used panels, re-certification remains crucial due to consumer skepticism regarding efficiency and reliability.[19] Certification processes should balance thoroughness with cost efficiency to ensure that second-hand panels meet performance and safety standards. Further research and study are needed in ways policy and regulations can encourage reuse of PV modules.

Patchwork of policies across states

Solar energy, especially at a utility scale, often crosses state lines, meaning varying regulations may impact compliance for businesses operating in multiple states. States with stricter EOL requirements may inadvertently drive waste to neighboring states with less stringent policies, causing "leakage" of discarded materials and undermining overall efforts to manage PV panel waste responsibly. For example, Minnesota's neighbors North Dakota and South Dakota have decommissioning requirements for large solar installations and Iowa and Wisconsin currently lack EOL policies for solar PV panels. This disparity may present a challenge for Minnesota as it implements its own policies. In the absence of federal legislation, any EOL policy in Minnesota must consider the risk of solar PV panels being discarded in neighboring states. Note, energy regulations and incentives are state specific and apply to in-state facilities or transmission, or to interstate transmission, and not to facilities located in other states.

2.3 Stakeholder Input on Policy Options

The Product Stewardship Institute (PSI) conducted multiple 1-hour interviews with EOL solar PV panel stakeholders in Minnesota and the United States. Interviewees were asked about the need for EOL solar PV panel policies, the policy scenarios being considered for Minnesota, and for any data or insights they could provide for the modeling outputs. Interviewees included solar manufacturers, installers, and recyclers; industry and community associations; local and state governments; and Tribes in Minnesota. A full list of interviewees can be found in Appendix A.2.0. Interviewees were also asked about potential benefits and negative impacts of solar PV panel recycling on communities including environmental justice communities. The findings on that topic are summarized in Section 4.5.1.

2.3.1 Consensus for EOL Solar PV Panel Policy

All interviewees agreed that there is a need to address the future volume of solar PV panels that will need EOL management. Solar manufacturers, installers, recyclers, and industry associations did not feel that there is an urgency to implement a policy in the near term except for a landfill ban. Solar installers, recyclers, and industry associations expressed uncertainty that the 20- to 25-year life expectancy for panels was a reasonable estimate for the study as many new panels have warranties of 30 years or more and it is unlikely that homeowners will replace panels unless there is a dire need (hail damage) or a significantly more efficient and cost-effective panels on the market. Local and state officials, an environmental group, an academic researcher, and officials from two Tribes in Minnesota felt that policies should be put in place now instead of waiting for the volume of EOL panels to grow. Citing lessons learned from past and current events, one interviewee from a tribe in Minnesota described the large stockpiles of old electronics they cleared from abandoned buildings when they first began recycling electronics, and several environmental nonprofit stakeholders cited a wind turbine junkyard, which was featured in a recent Star Tribune[20] article, that materialized in a small Minnesota town south of Minneapolis as examples of the risks of not planning for end-of-life management of solar PV panels.

2.3.2 Input on Policy Scenarios by Stakeholder Group

Interviewees' thoughts on the policy scenarios varied by stakeholder group and by the solar PV panel sector to which the policies would apply (i.e., residential vs. utility).

- State and local government officials generally agreed that a permittee-funded or an EPR approach would be necessary to create a program to address all EOL solar PV panels.

- The academic researcher favored the EPR approach, since manufacturers reap the most profit and because installers/permittees are economically squeezed in the current market. When asked directly about a hybrid model, whereby decommissioning would be required for utility-scale arrays and an EPR model would be used for smaller rooftop systems, the academic and environmental nonprofit interviewees expressed openness to exploring this approach.

- Manufacturers, installers, recyclers, and industry associations expressed confidence that requiring decommissioning plans and enforcing a landfill ban with recycling targets would be effective. Manufacturers, installers, recyclers, and industry associations agreed that a fee-based program of some type may be needed to enable EOL management for residential/rooftop solar PV panels.

- The interviewees from two Tribes in Minnesota noted that they are not subject to Minnesota state law and their participation in any program would be voluntary. One Tribe finds the advanced recycling fee they assess for electronics recycling to be effective and suggested it could be a policy model for EOL solar PV panels.

Most of the interviewees acknowledged that the significant economic and logistical differences between deinstalling and recycling utility-scale solar arrays and smaller rooftop arrays may warrant different end-of-life management approaches. Utility-scale projects have more EOL value and are more cost efficiently collected and transported than the smaller, distributed net-meter installations that have a higher cost to value ratio. A summary of key feedback from stakeholders for (1) decommissioning plans, (2) a landfill ban with recycling targets, (3) permittee and ratepayer funded model, and (4) Extended Producer Responsibility are described in the list below.

1. Well-funded decommissioning plans have support, but there is no agreement yet on the appropriate megawatt capacity threshold for decommissioning:

   Manufacturers, installers, recyclers, and industry associations were supportive of the use of decommissioning plans with financial assurance tools that allow the installation owner to build up the needed funds over the life of the installation. Some nonprofit organizations were also supportive of the use of decommissioning plans with financial assurance tools, provided the threshold for decommissioning was lowered; suggestions included 10 MW, 5MW, and 1 MW. Interviewees from two Tribes in Minnesota expressed interest in reevaluating and reducing the megawatt threshold requirement for decommissioning to cover more installations. They also suggested that solar installations located near each other and/or owned by one entity could be combined for the purposes of meeting the minimum megawatt threshold for decommissioning. Both Tribes interviewed have installed solar arrays: one Tribe interviewed owned two solar arrays, one 3.2 KW and the other 6 KW, and has a long-term lease on a 3 MW array; the other has a solar array that uses panels from Minnesota-based manufacturer Heliene. State government officials expressed concerns that lowering the megawatt threshold from 50 MW would bring more projects under state decommissioning requirements instead of local government requirements and oversight. They, and local governments interviewed, suggested that some local governments in Minnesota would be reluctant to give up their authority to determine decommissioning requirements. Other interviewees suggested that local governments in Minnesota would be glad to be free of oversight responsibility for decommissioning. Most interviewees agreed that decommissioning would not be an effective policy for managing residential roof-top solar PV panels.

2. A landfill ban with recycling targets has consensus support:

   All interviewees agreed that a landfill ban with recycling requirements was needed and would help supplement other policy scenarios. Installers reported that most large project installers were requiring recycling in their decommissioning plans already and were supportive of ensuring a requirement for all installations. Interviewees expressed that a landfill ban would need regulations and enforcement to ensure EOL panels are not shipped out of state to be landfilled. Interviewees also expressed strong interest in ensuring that solar PV panels are sent to reuse and recycling facilities where they will be handled safely and recovered to the highest and best use in regions with protective health, safety, and environmental regulations. Installers of large installations noted that they would support regulations for ensuring the responsible and proper recycling of panels, for example through third-party certification programs.

3. The mechanics of a permittee or ratepayer funded model were unclear and complex. The following feedback from stakeholders resulted in elimination of the ratepayer scenario and changes to the permittee scenario that was ultimately modeled:

   Manufacturers, installers, recyclers, and industry associations did not feel that a fee was needed to cover the cost of installations that already required a decommissioning plan, but acknowledged funding would be needed for a program for residential rooftop panels. One Tribe noted that their advanced recycling fee for electronics works well and could be a model for solar recycling. State and local government officials agreed that a fee-based program could work for residential/rooftop solar PV panels but were skeptical that a utility rate to fund the program would be politically feasible. The environmental nonprofit interviewees preferred to see no cost burden for solar recycling on individual households and small businesses. However, they also noted that because the utility commission is closely monitored by their organization and scrutinized by the public, they would not expect ratepayers in Minnesota to be overcharged. They noted, though, that it would be politically problematic, as any increased costs would be blamed on policy makers supporting renewable energy. Another nonprofit organization pointed out that largely rural, off-grid solar arrays would be free-riders in a ratepayer-funded system, since they are not ratepayers. The academic researcher interviewed discouraged a permittee-funded model, since installers are economically squeezed in the market.

4. EPR programs as a concept have support although the scope needs better definition:

   State and local government officials currently implementing EPR programs for solar PV panels supported an EPR approach but reported challenges registering foreign manufacturers for their programs. The agencies were moving down the hierarchy of responsible parties to hold distributors, project developers, and installers responsible for funding their programs, as stipulated in their laws. Solar PV panel manufacturers, installers, recyclers, and industry associations interviewed were not supportive of an EPR approach. The academic and environmental nonprofit interviewees were all supportive of an EPR approach, if not for all solar PV panels, then for residential rooftop installations. Environmental nonprofits, the academic researcher, and members of Tribes interviewed all expressed an interest in EPR policy because it can incentivize the design of solar PV systems that are less toxic, can be reused, and can be recycled, ideally infinitely as aluminum can be.

Interviewed stakeholders were also asked about the potential benefits and negative impacts of solar PV panel recycling on Minnesota communities, including environmental justice communities. Findings on this topic are described in detail in Section 4.5. The five environmental justice considerations that were raised most frequently were:

- Solar EOL policy should ensure use of responsible end markets,
- Solar EOL policy should ensure the occupational health and safety of solar recycling workers,
- Emissions from transportation should be minimized,

- Communities should be engaged early and often in the siting, permitting, and oversight of solar PV recycling facilities, and
- Materials recovery and recycling should be maximized.

With this context from stakeholders across the value chain along with Eunomia's evaluation of policy options, the project team and MPCA determined five policy scenarios, plus a baseline "no new policy" scenario, to model within this study. These policy scenarios, and the assumptions underlying each, are described in detail in Section 3.3.

3.0 Modelling Approach

3.1 Purpose

Eunomia was tasked with modelling a cost benefit analysis of different policies to address the generation of end-of-life solar PV panels until 2050 in Minnesota. Eunomia undertook a quantitative analysis which projected the generation of end-of-life solar PV panels until 2050, and the cost of subsequent strategies targeted at collecting and recycling these solar PV panels. The process of determining which policy mechanisms to model is described in Section 2.0.

The modelling was divided into two phases:

1) **Generation Forecasting:** First, Eunomia estimated the quantity of end-of-life solar PV panels in Minnesota until 2050. This was done by using data from the Minnesota Department of Commerce on historical solar PV panel installations, as well as forecasting future installations within the state. Eunomia then applied useful lifetime assumptions to the installed solar PV panels to estimate solar PV panel waste generated.

2) **Policy Cost-Benefit Analysis:** After the generation of solar PV panels was modelled, Eunomia estimated the cost of managing, collecting, and recycling the solar PV panels under five different policy scenarios, as well as analyzing a “no new policy” option. The modeled scenarios are described in more detail in Section 3.3.

This section first describes the methodology to estimate the generation forecasting and then discusses the approach to modelling five different scenarios.

3.2 Generation Modelling

3.2.1 Data Gathering and Research

To understand and evaluate the level of end of life (EOL) solar PV panels that are currently generated in Minnesota and to forecast the expected number of PV panels that will reach EOL from 2024-2050, Eunomia used both historic and forecasted installation data. The project team utilized data from both primary and secondary research for installations which included:

Desktop research and outreach: The project team analyzed and gathered data from several useful reports and databases, such as:

- Documents provided by MPCA:
  - MPCA 2019 Presentation on EOL Solar PV Panels to the Minnesota Solar Energy Industries Association (MnSEIA).[21]
  - South Carolina Department of Health and Environmental Control Final Report on End-of-Life Management of Photovoltaic Modules and Energy Storage Systems.[22]
- Additional research and outreach: The project team reviewed published reports and studies, and when little data was available, called on solar PV panel installers, EOL solar PV panel stakeholders and other EOL solar PV panel subject matter experts, throughout the U.S. to gather more information on EOL solar PV panel forecasting and recycling.

Survey: The project team sent a comprehensive survey to members of a non-profit organization, Minnesota Solar Energy Industries Association (MnSEIA). The goal of the survey was to help inform the analysis, including about panel installation, collection and decommissioning. Questions focused on the following topics:

- Current collection methods of solar PV panels at EOL
- Cost information on deinstalling, decommissioning, transporting, dismantling, and recycling of solar PV panels
- Past installations and deinstallations
- Future installations and deinstallations

In total, two MnSEIA members responded to the survey. Their responses are confidential, but a full list of the survey questions asked is included in Appendix A.1.0.

Interviews: The project team conducted comprehensive interviews with EOL solar PV panel stakeholders in Minnesota and the United States. Interviewees were asked about the need for EOL solar PV panel policies, the policy scenarios being modelled for Minnesota, and any data or insight they have for the modelling outputs such as:

- Current costs/value associated with recycling solar PV panels
- Current values for reusing solar PV panels
- Factors that determine recycling costs the most (e.g. collection, transportation, processing of EOL solar PV panels, etc.)
- Impact of solar PV panel recycling mandates in Minnesota

In total, sixteen EOL solar PV panel stakeholders were interviewed. Key findings from the interviews are summarized in Appendix A.2.0.

3.2.2 Solar PV Panel Installation and Forecasting

Eunomia estimated solar PV panel EOL generation by first compiling historic installations in the state of Minnesota, and subsequently projecting future installations until 2050. After doing so, Eunomia could apply useful lifetime assumptions to these installations.

3.2.2.1 Historic Installations

The first step in Eunomia's modelling approach was to summarize the historic installation data within the state. This data comes from two sources:

1) The Minnesota Department of Commerce: the Department tracks every solar installation that is under 10 MW of capacity within the state.
2) The U.S. Energy Information Administration: the US EIA tracks solar installations which are above 10 MW nationally, by state.

This data allowed for an estimate of total MW installed across five different sectors. That data is summarized in the total row of Table 6.

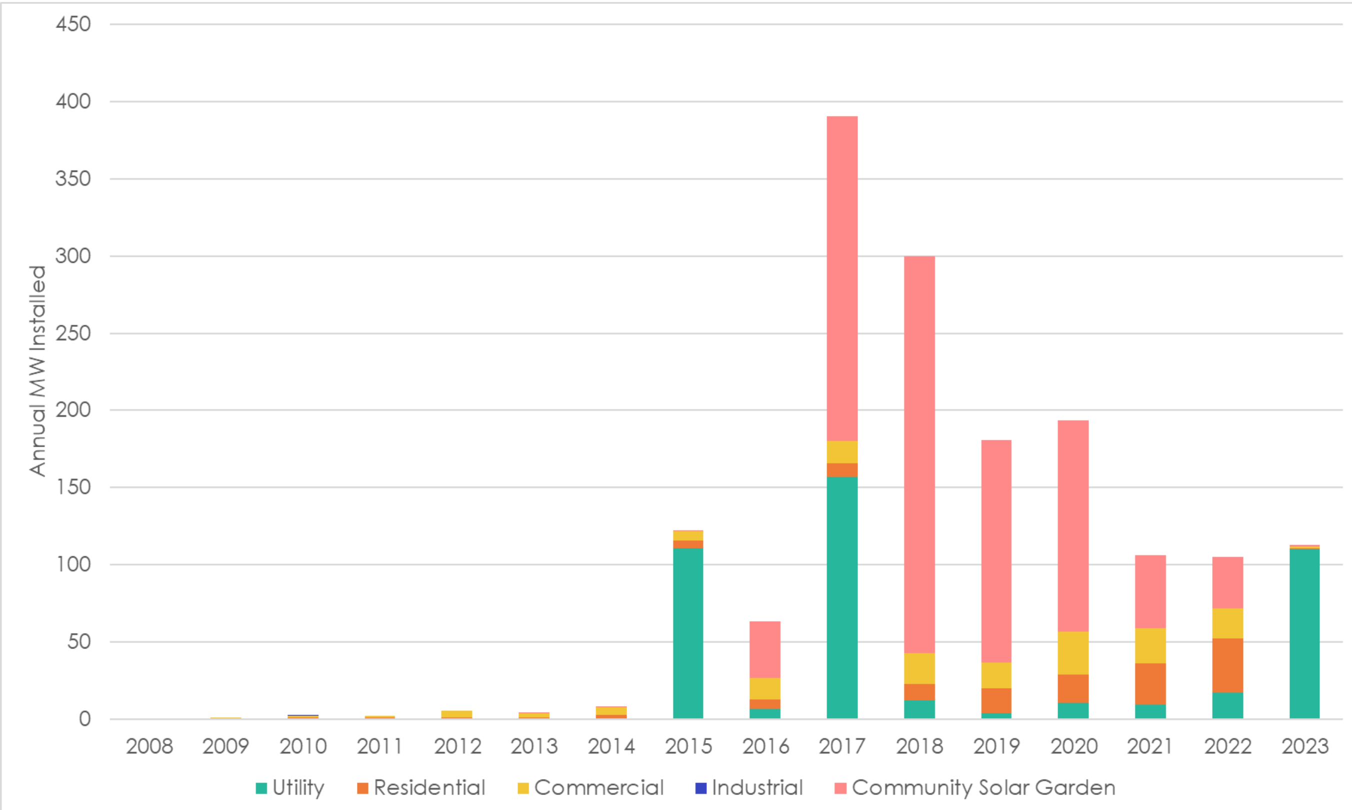
Table 6. Cumulative Installations of Solar Power through 2023, by Sector

Sector	Sector Description	Cumulative MW Installed through 2023 (MW)	% of Solar PV Panels < 1 MW	% of Solar PV Panels between 1 and 50 MW	% of Solar PV Panels > 50 MW	% of All MW Installed
Utility	Solar installations for grid sales.	440	0.10%	17.32%	10.28%	28%
Residential	Solar installations on residential households, rooftop solar.	140 [<40kw]	7.43%	0%	0%	7%
Commercial	Solar installations on commercial properties, rooftop solar.	160 <10MW	7.53%	2.42%	0%	10%
Industrial	Solar installations for industrial locations, meant for internal use.	< 10	0.01%	0%	0%	<1%
Community Solar Garden	Solar installations for a specific group of households, communities, not for other public consumption. Solar field rather than rooftop.	870 [typically 0.5-1MW]	6.39%	48.51%	0%	55%
Total		**1,600**	**21.47%**	**68.25%**	**10.28%**	**100%**

As shown in Table 6, over half the installations in the state through 2023 were for Community Solar Gardens (CSGs), with Utility installations representing about 25% of installations. Residential and commercial installations have a similar quantity of MW installed at 140 and 160, respectively. Both represent about 10% of all solar installations.

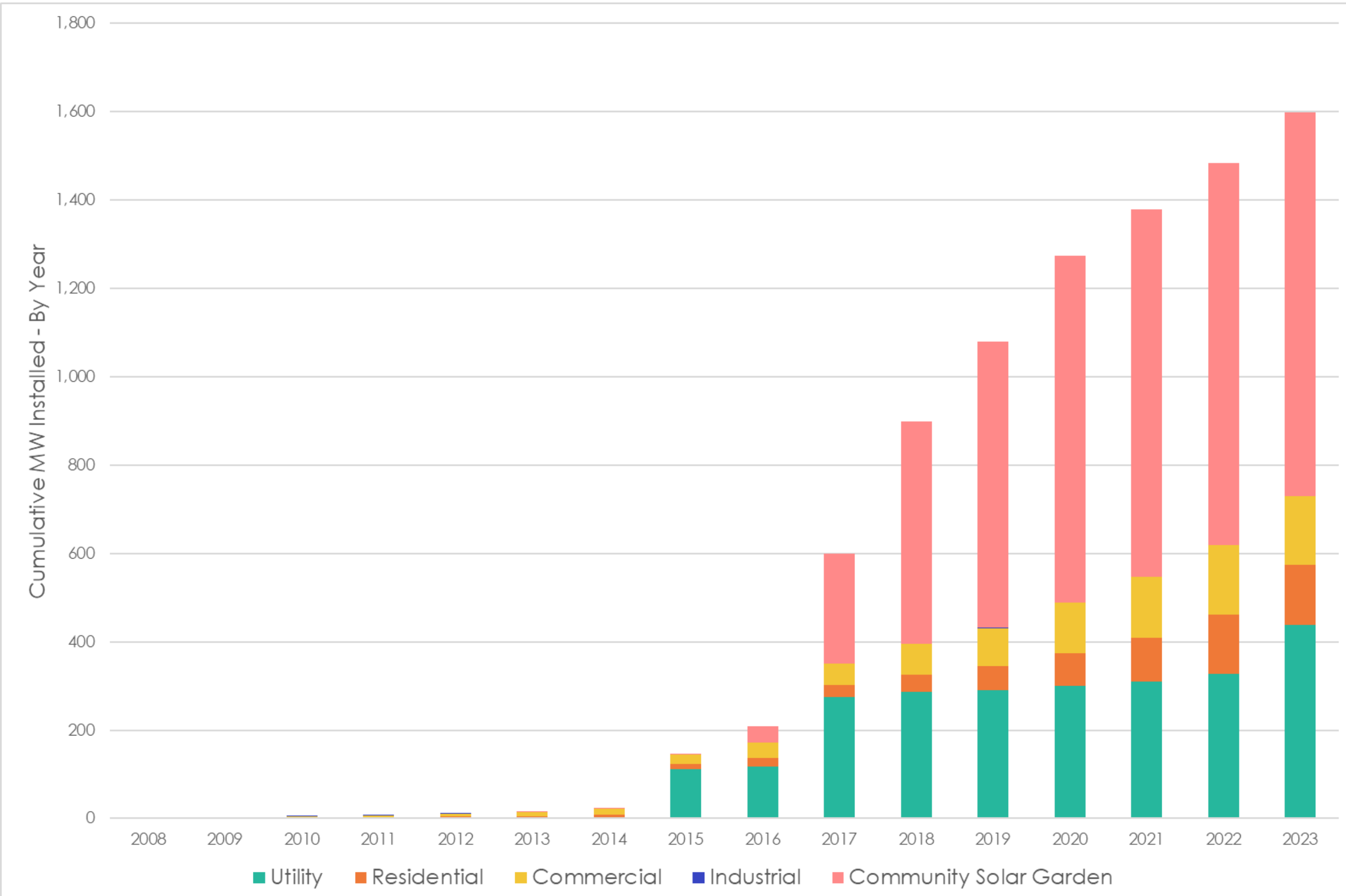
The installations by sector by year can be seen in Figure 25 and cumulatively by year in Figure 26.

Figure 25. Historic Annual Solar Installations by Sector by Year in Minnesota



Source: Minnesota Department of Commerce data

Figure 26. Cumulative Historic Solar Installations by Sector by Year in Minnesota



Source: Minnesota Department of Commerce data

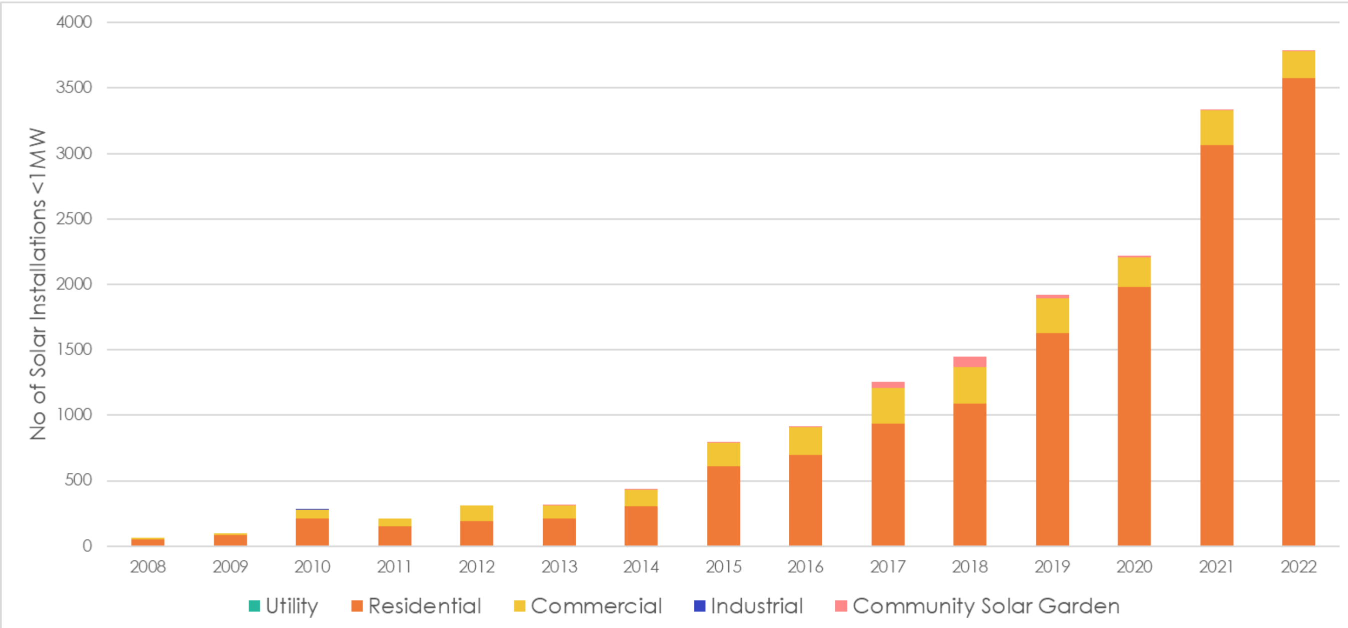
Most installations occurred between the years of 2014 and 2023. There are spikes in installations of Utility solar in 2014, 2017 and 2023. CSG installations were installed at an average of 124 MW per year between 2016 and 2022.

Eunomia also analyzed this historical installation data to evaluate the number of installations or projects completed, so that future installation forecasts could be split into their use sectors (utility, residential, commercial, industrial, community solar garden). The number of installations (number of projects installed) in each sector from 2008 to 2023 are shown by sector in Figure 27 for installations <1MW, Figure 29 for installations between 1MW-10MW and Table 7 for installations >10MW, and are shown cumulatively in Figure 28 for installations <1MW and Figure 30 for installations between 1MW and 10MW.

Installations below 1 Megawatt

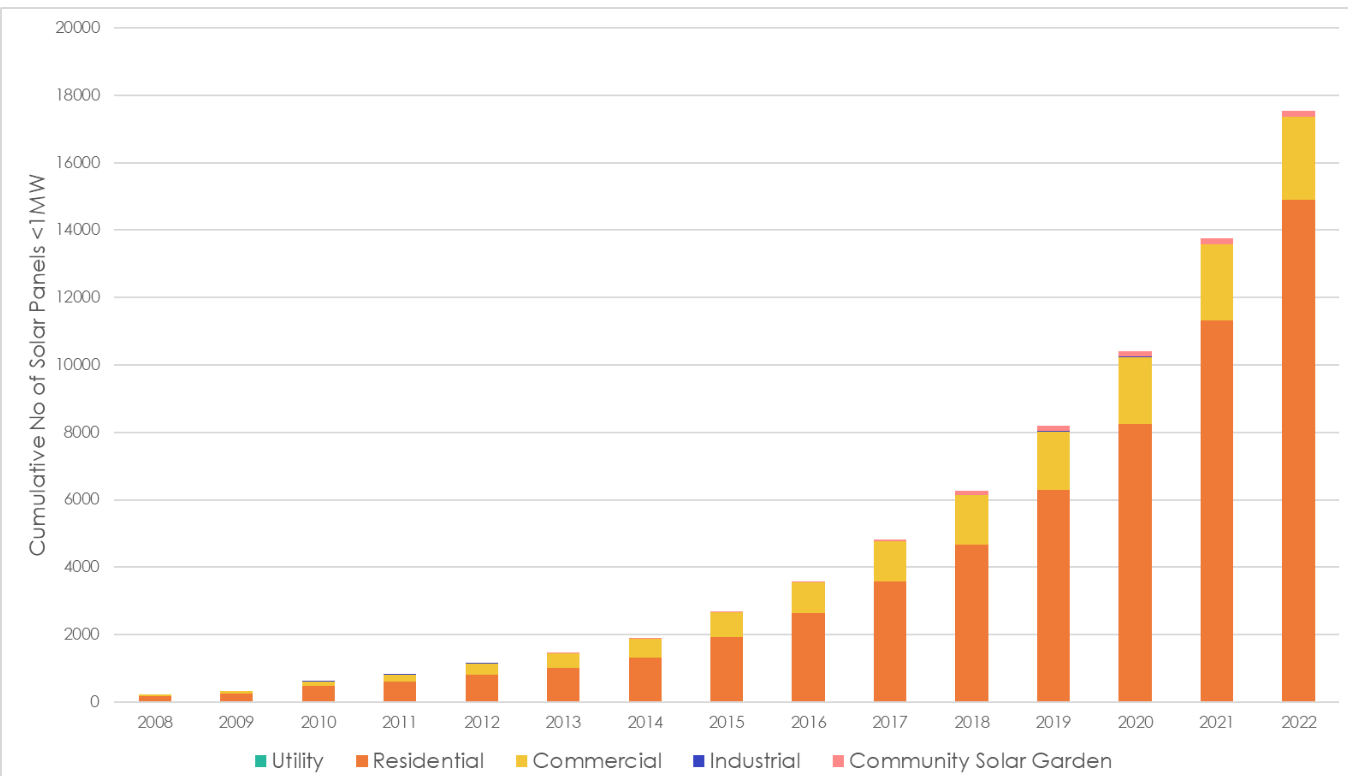
Figure 27 shows the total number of annual solar installations <1MW in Minnesota from 2008-2023 and Figure 28 shows the cumulative number of annual solar installations <1MW from 2008-2023. In these figures, the residential sector makes up the greatest number installations, increasing from 48 installations in 2008 to 3,579 installations in 2022, before dropping to 105 in 2023. The commercial sector increases from 19 installations in 2008 to 268 installations in 2022 and drops to 201 installations in 2023. There are fewer than 30 utility installations that are less than 1 MW in capacity, and only 180 CSG installations.

Figure 27. Number of Historic Annual Solar Installation Projects <1MW by Sector by Year in Minnesota



Source: Minnesota Department of Commerce data

Figure 28. Cumulative Number of Historic Annual Solar Installation Projects <1MW by Sector by Year in Minnesota

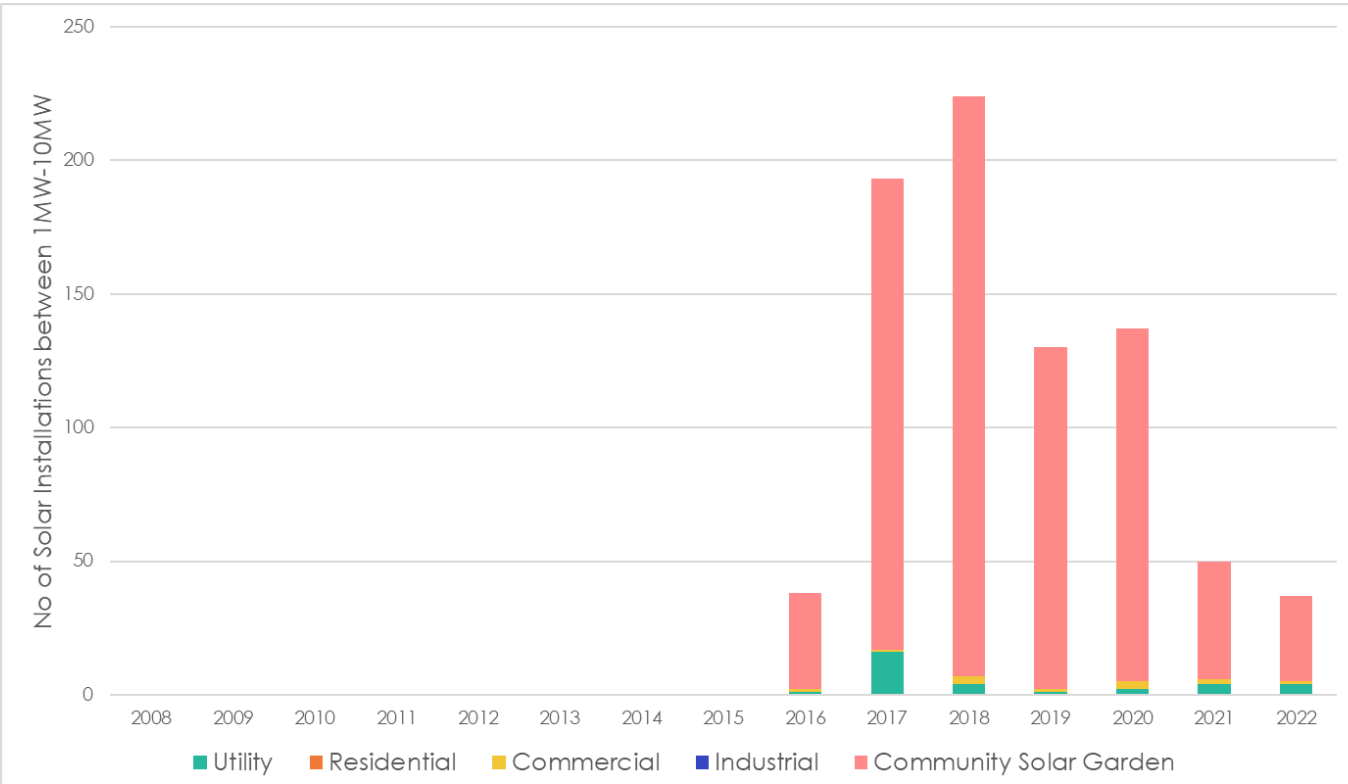


Source: Minnesota Department of Commerce data

Installations between 1 and 10 Megawatts

Figure 29 shows the total number of annual solar installations between 1MW to 10MW 2023 and Figure 30 shows the total cumulative number of solar installations between 1MW to 10MW in Minnesota from 2008-2023. Community solar garden installations make up the greatest number of installations, and this is the most common size band for CSGs. In 2018, there were 217 community solar garden installations in Minnesota between 1 and 10 MW.

Figure 29. Number of Historic Annual Solar Installation Projects between 1MW-10MW by Sector by Year in Minnesota



Source: Minnesota Department of Commerce data

Figure 30. Total Cumulative Number of Historic Annual Solar Installation Projects between 1MW and 10MW by Sector by Year in Minnesota

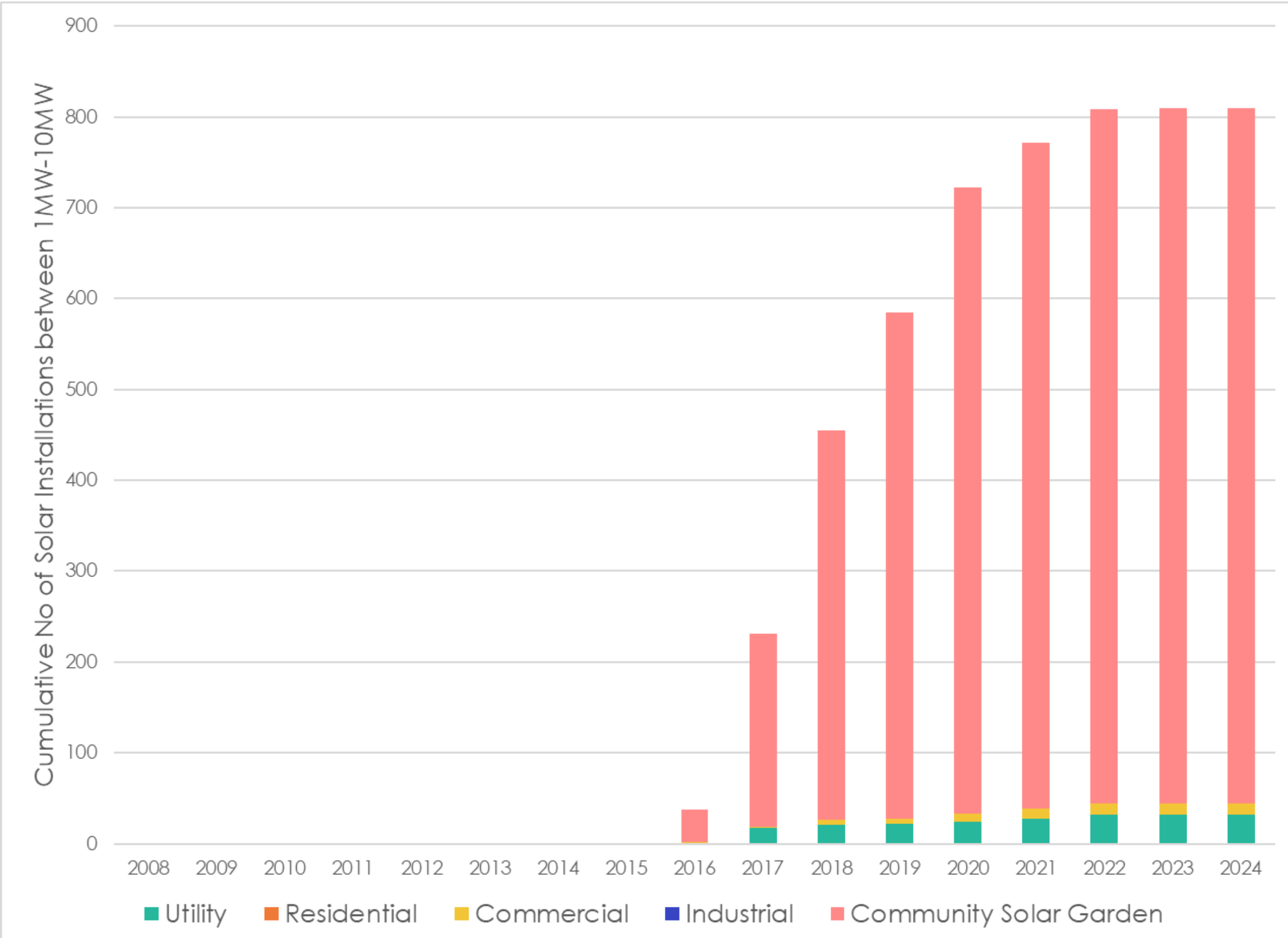


Table 7. Number of Historic Annual Solar Installation Projects >10MW by Sector by Year in Minnesota

Year	No. of Installations >10MW
2016	2
2017	4
2023	3

Source: Minnesota Department of Commerce data, Energy Information Agency (EIA) data

Table 7 shows the total number of annual solar installations >10MW and shows the total cumulative number of annual solar installation >10MW, in Minnesota from 2008-2024. The utility sector is the only sector that had installations >10MW in Minnesota in these years. In 2016, there were two utility scale solar installations >10MW, one with a 10.9MW capacity and another with a 100MW capacity. In 2017, four utility scale solar installations were installed. Three utility solar installations above 10 MW were installed in 2023. The 2023 installations have 15.2MW, 49.9MW, and 45MW capacities.

Table 8. Total Number of Solar PV Panel Installations, 2008 to 2023

Sector	<1MW	1MW-10MW	>10MW
Utility	18	32	3
Residential	14,985	0	0
Commercial	2,459	12	0
Industrial	3	0	0
Community Solar Garden	178	766	0

Figure 31. Total Capacity of Solar PV Panels Installed by Sector, 2008 to 2023

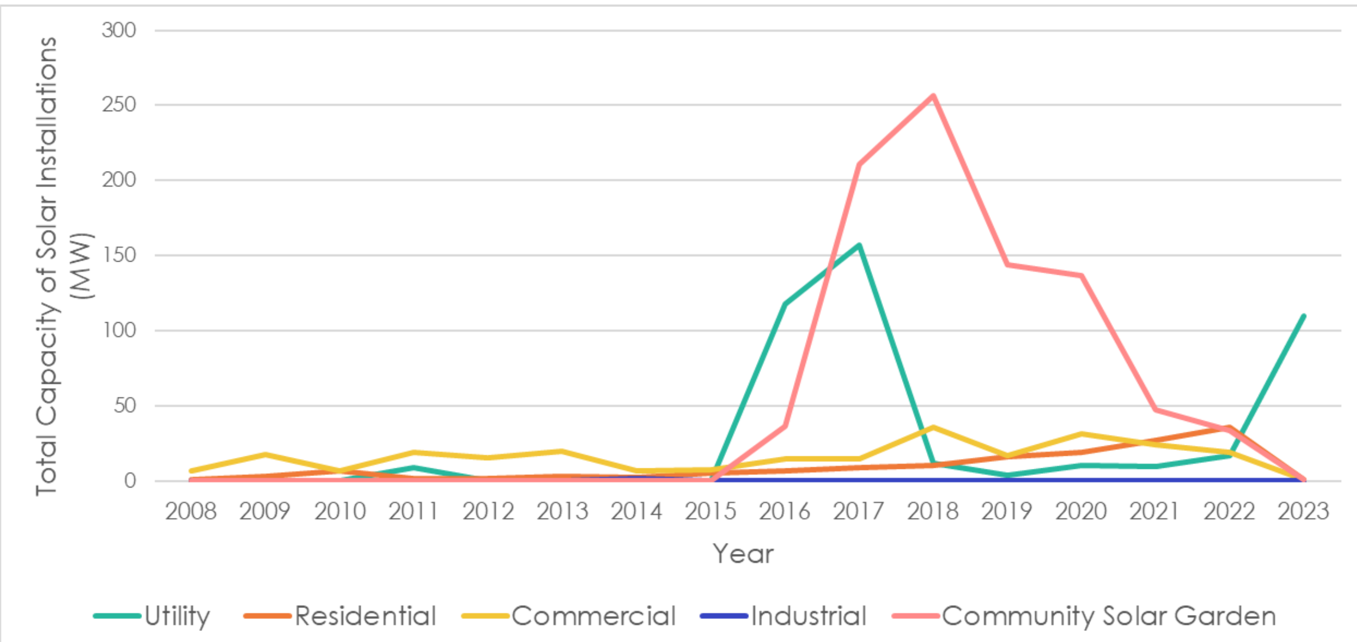


Figure 31 shows the total capacity of solar PV panels installed by sector from 2008 to 2023. The is a spike in the total capacity of solar PV panels installed in the utility sector in 2016 as a result of the 100MW North Star Solar Project that was completed in 2016, near North Branch Minnesota. This spike increases in 2017 as a result of the ~60MW Marshall Solar PV Park, which was completed in 2017, combined with ~90MW of other utility installations <10MW. The community garden sector as the greatest total capacity of solar installations from 2017 to 2022. In 2017 the total capacity of community solar garden installations was ~210MW and increased to ~250MW in 2018 before decreasing to ~140MW in 2019.

3.2.2.2 Forecasted Installations

The second step in Eunomia's modelling approach was to calculate the projected future solar PV panel installations in Minnesota. Using state clean energy and solar targets, utility company Integrated Distribution Plans (IDPs) and historical data on the average MWs per year of solar installed in MN, the modelling team estimated the total MWs of solar to be produced from 2024-2050.

The following key assumptions were made:

- Population growth rate in Minnesota of 0.2% per year.[23]
- Community Solar Garden Caps are met (100 MW/year until 2027, 80 MW/year from 2027 to 2030).
- Conservative solar PV panel design and efficiency increases such that panel weights per megawatt decrease by 0.05% per year from 2024 to 2050, reflecting a smaller trend compared to the period of 2014 to 2030 in IRENA's 2016 paper.[24]
- Commercial, residential and industrial average installations per year continue if Solar Rewards are available (at least until 2034).
- The solar share of carbon free electricity in 2030 (~15%) would be the same in future years.

Calculating power forecasts for the periods 2024-2030, and 2031-2050 were done with different methodologies. This is for two primary reasons:

1) Utility companies have announced their installation forecasts up to 2030, offering greater clarity on forecasted installations for this period.
2) There is a 10% solar target for Utility companies to meet in 2030. After 2030, Minnesota has "Carbon Free" electricity goals, however there is less certainty or documentation on how much solar power is projected to be installed and therefore the project team used two different methods for the two periods.

Methodology – through to 2030

A combination of Integrated Resource Plan (IRP) reports from utility companies outlining their solar power targets, as well as state legislation mandating 10% of utility sales be solar electricity by 2030, were used to estimate solar generation for each year up to 2030. Utility installations were then broken down into community solar garden installations or regular utility installations based on the assumptions that community solar garden caps are met. Community solar garden caps are the total annual capacity of new gardens that Minnesota's Department of Commerce can approve. These caps are outlined in the Legacy CSG Program which was passed in 2023 and sets a 100MW cap from 2024-2026, an 80MW cap from 2027-2030, and a 60MW cap each year after 2030[25]. Residential, commercial, and industrial installations were based on average annual installations in years where solar rewards are in place.

Integrated Resource Plan (IRP) targets are shown in Table 9.

Table 9. Figures from Integrated Resource Plans

Law/Source	Target Year	Target power type	Goals/Target
Otter Tail Power Company	2022-2029	Solar Resources	Develop plans for 200-300 MWs of Solar Resources
Xcel Energy	2030	Solar Resources	1,400 MWs
Dakota Electric - Great River Energy	2035	Carbon Free Resources	90%
Minnesota Power	2030	Solar	200 MWs

While Dakota Electric has an announced target of 90% of retail electric sales to be 90% carbon-free by 2035, no forecasted installation figures could be found for 2030. It was therefore assumed 0 MW of additional solar power would be installed by Dakota Electric by 2030.

In total, these IRP's add 850 MW of retail electric solar power installations to Minnesota power supply by 2030.

In addition to the retail electricity installations, Eunomia also projected installations based on average annual installations during Solar Rewards years for commercial and residential properties. The total project installed capacity through 2030 is shown in Table 10.

Table 10. Projected Solar Installations through 2030

Sector	Projected Additional MW Installed (rounded to nearest 100)	Main Data Source/Method
Utility	1800	Integrated Resource Plans
Residential	100	Average annual installations during Solar Rewards periods
Commercial	100	Average annual installations during Solar Rewards periods
Industrial	0	Average annual installations during Solar Rewards periods
Community Solar Gardens	600	IRP's – CSG installations assumed to be part of announced solar capacity installations from utilities
Total	**2,600**	

In total, an estimated 2.4 GW of solar power capacity is projected to be installed in Minnesota from 2024 to 2030. CSGs will continue to be the greatest source of installations, even with annual installation caps. Combined with historic installations, a total of 2.6 GW of solar power capacity is projected to be installed by 2030. This represents 22% of all power capacity in the state (the EIA reported a total electric utility industry capacity of 18.4 GW in 2022).[26]

Methodology – 2031 and beyond

A combination of IRP reports from utility companies outlining their solar power targets, as well as a Minnesota target of 100% of electricity being Carbon Free by 2040, were used to estimate solar generation for each year from 2031-2050. It was assumed that Solar would remain the same share of carbon free electricity as it is in the baseline year.

Table 11 shows the total electric power capacity by carbon free energy source for Minnesota in 2022. This data was taken from the U.S Energy Information Administration (EIA).[27] Eunomia used this capacity data to calculate what percent of Minnesota's energy capacity came from solar energy in 2022.

Table 11. Electric Power Capacity by Carbon Free Energy Source in Minnesota in 2022

Power Source	2022 Capacity (MW)	% of Carbon Free Total
Solar	1,143.2	15%
Wind	4,828.7	62%
Biomass	110.6	1%
Nuclear	1,657.0	21%
Battery	16.0	0%
Total	**7,756**	**100%**

Utility installations were then broken down into community solar gardens or regular utility installations based on the assumptions that community solar garden caps are met. Residential, commercial, and industrial installations were based on average annual installations in years where solar rewards are in place.

The total installations for 2031-2050 are shown in Table 12, along with the total installations from 2024-2030, and finally the cumulative total from both periods.

Table 12. Total Projected Solar Installations

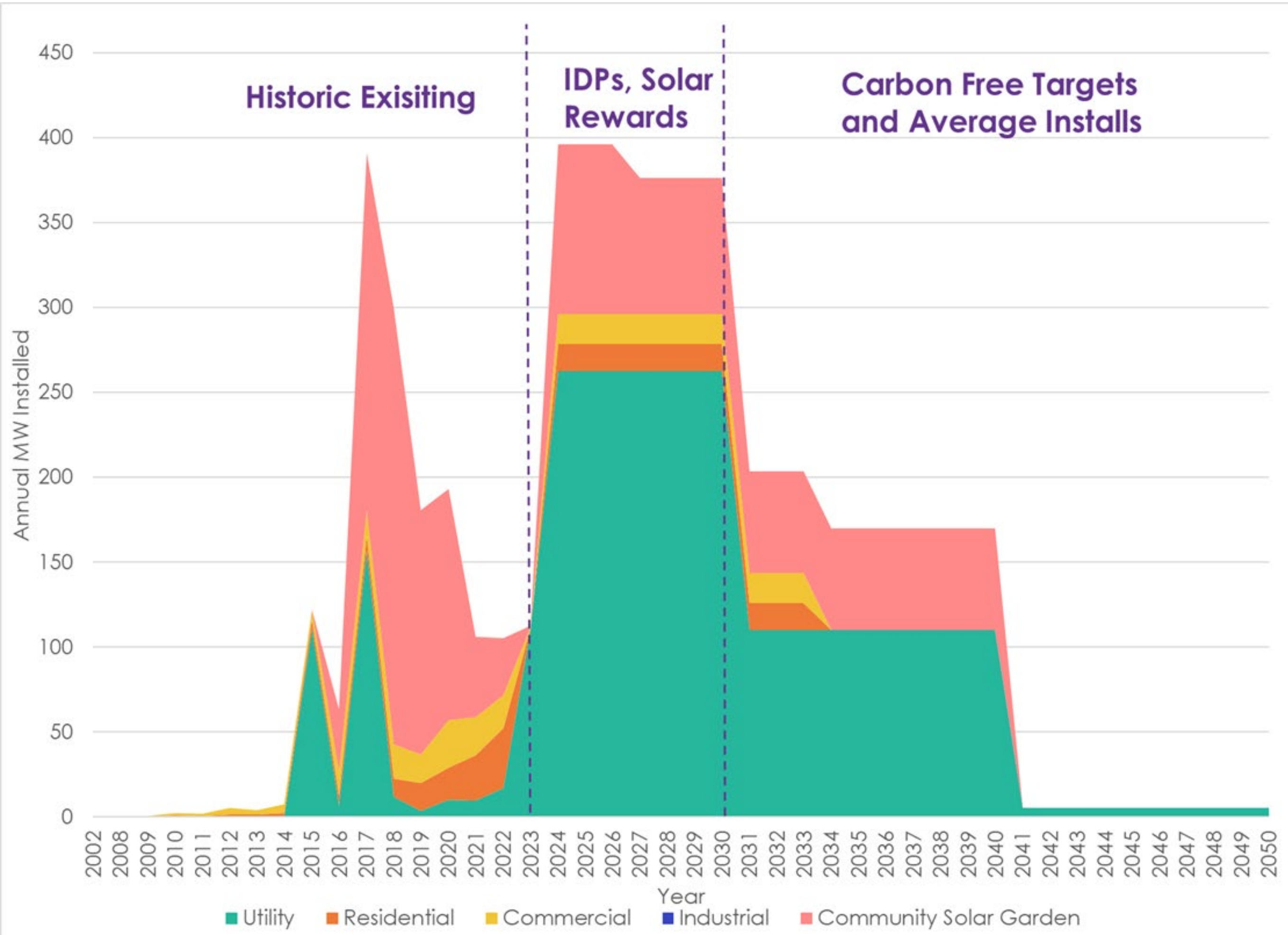
Sector	Projected Additional MW Installed 2024-2030 (rounded to nearest 100)	Projected Additional MW Installed 2031-2050 (rounded to nearest 100)	Total Additional MW Installed, 2024-2050	Total MW of Solar Capacity in Minnesota 2050
Utility	1,800	500	**2,300**	**2,700**
Residential	100	0	**200**	**300**
Commercial	100	100	**200**	**300**
Industrial	0	0	**0**	**0**
Community Solar Gardens	600	600	**1,200**	**2,100**
Total	**2,600**	**1,200**	**3,900**	**5,400**

Source: Department of Commerce historical installation data, Utility IDP's, EIA Data, Eunomia Modelling, totals may not add due to rounding.

Most installations are expected to occur between 2024 and 2030, with 2.6GW being installed in this period. From 2031 to 2050, a projected 1,200 MW are installed. A total of 3.9 GW is expected to be installed between 2024 and 2050, bringing the statewide total of solar power capacity to 5.4 GW. Assuming power generation and population grow in tandem, 5.4 GW of solar power would represent 25% of statewide electricity capacity from all electricity sources. Forecasting is based on knowns, which are better understood through 2030 and 2040, and then less known in later years. Forecasts of installation and removal may not be accurate, but estimated recovery percentages and per panel costs are likely to be close to estimates in this study.

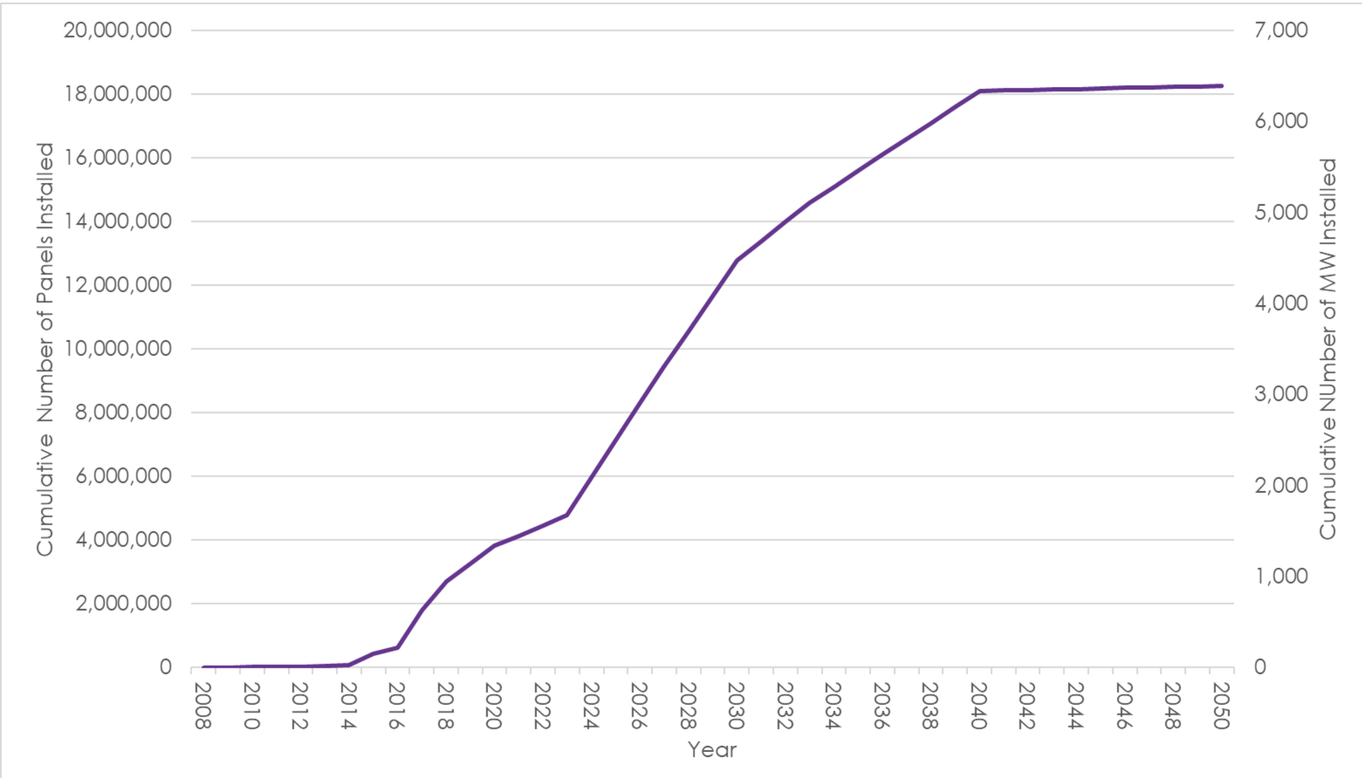
A final summary of all existing and projected annual solar installations, along with the predominant estimation method, are shown in Figure 32 and cumulatively in Figure 33. These installations include *new* installations only (net new capacity installed), they do not include swap outs of existing installations.

Figure 32. Annual Installed Solar Capacity, 2008-2050, Purple Text Shows the Predominant Calculation Methodology for Each Time Period



The cumulative installations of wattage and number of solar panels can be seen in Figure 33 below. Solar capacity after 2040 is 'flat' in part because the drivers for installations after 2040 are not well known or understood at this time. Additionally, larger numbers of panels are coming out of service, offsetting installations to an extent that is difficult to forecast at this time. Cumulative capacity may increase significantly after 2040 but at this time the drivers and their potential impacts are unknown.

Figure 33. Cumulative Solar Capacity 2008-2050



3.2.3 End of Life (EOL) Estimates

3.2.3.1 MW to Tonnage Calculation

To estimate the total EOL tonnages which are projected to arise from the existing and modelled solar installations, the total MWs for each installation type were converted into number of panels and weight in tons. This was done by multiplying the number of MW installed by an assumed number of panels per MW. This is illustrated in the equation below:

$$Tonnage\ of\ Solar\ Panels = MW * Panels\ per\ MW * Weight\ per\ Panel$$

Eunomia used an average of 3,000 panels per MW, consistent with data used by MPCA in their Solar Panel Whitepaper.[28] Eunomia divided the total MW by this figure to arrive at total number of panels installed. Eunomia could then use an average weight per panel to estimate the total tonnage of panels installed. An average weight of 45 pounds per panel was used for silica panels, while an average weight of 80 pounds was used for cadmium-based panels.[29] [30] This weight was dropped to 40 pounds per panel for residential solar PV panels, consistent with panels in that sector being lighter than non-residential solar PV panels.[31]

3.2.3.2 Solar PV Panel Useful Life and Damages Calculation

To estimate how many solar PV panels will reach their end of life from 2024-2050, the previously calculated historical and forecasted solar tonnage data was entered into an average lifespan matrix with damage and breakage assumptions. An increase in solar PV panel efficiency overtime was assumed. The useful lifetime of a panel was sourced from NREL's PV ICE tool, while damage or failure rates for the years leading up to useful lifetime were taken from both NREL's PV Ice tool and IRENA's 2016 report on Solar Panels End of Life. These assumptions are discussed further below.

IRENA's 2016 report gives the following assumptions shown in Table 13 for losses in its "early-loss" scenarios:

Table 13. IRENA Early Loss Assumptions for Solar PV Panels[32]

Period of Losses of Cohort Installation	% Lost
Installation/transport damages	0.5%
Further Losses within 2 years	0.5%
Further Losses after 10 years	2%
Losses after 15 years	4%

In total, 4% of installed panels were lost before 15 years in the IRENA study. Eunomia used these assumptions for solar PV panel losses before 15 years, as there is limited data on existing solar PV panel failure rates.

For the number of years which a solar PV panel that is not damaged has a useful lifetime, Eunomia used data from NREL's PV ICE tool. NREL's PV ICE Baseline Modules Mass Flow data assumes that the useful lifetime for solar PV panels that were installed between 2014 to 2020 is between 26 and 35 years. Thirty-five years is the longest lifetime within the dataset.[33] This is shown in Table 14.

Table 14. Subset of NREL PV ICE Solar PV Useful Lifetime Data

Installation Year	Useful Lifetime in PV ICE Dataset (years)
2014	26
2016	28.7
2018	31
2020	35

Most of the panels that will reach the end of their life within the study period (between 2025 and 2050) will have been installed between 2015 and 2030. Therefore, Eunomia used 25-35 years (the typical life of panels installed between 2014 and 2020) as the useful life range of a panel.

Two key assumptions have therefore been selected for the EOL calculations:

- A loss of 4% of panels before year 15 from IRENA's study.
- A useful lifetime of 25-35 years for panels which are not damaged or have panel failures.

The period of time between the IRENA study losses (year 15) and the start of useful life losses (25 years), is still left in need of an assumed annual loss. PV ICE does not include weather related losses in its data; therefore, Eunomia took a conservative approach to estimating the proportion of solar PV panels lost before useful life.

This approach begins by looking at the "cohort failure" statistics from PV ICE. PV ICE has the following assumptions on cohort solar PV panel losses, shown in Table 15.

Table 15. NREL PV ICE Data on cohort Solar PV Panel Losses

Cohort Installation Year	Number of Years after installation at which 50% of cohort modules have failed
2014	28
2016	28
2018	28
2020	33
2022	33
2024	33
2026	33

The chart above indicates that for modules installed in 2018, 50% of the modules will have failed by 2046 (28 years later). For a solar PV panel cohort installed in 2018, using the assumptions thus far from both IRENA and PV ICE, this means that:

- 4% of panels will be replaced by 2033 (IRENA, 2016)[34]
- Between 2033 and 2046, 46% of the cohort will also be replaced (PV ICE)[35]

The majority of solar PV panels that are replaced after 2033 from the 2018 cohort group will likely occur around the useful lifetime of the panels (2043-2053, 25-35 years after installation). The PV ICE data does not provide estimates for weather related damage or breakages. Eunomia therefore assumed a small proportion each year will need to be replaced due to these external factors. To reflect this, Eunomia assumed that 0.5% of panels are replaced each year between 2033 and 2043 from damage and weather-related breakages. This yields a total loss of 5% of the cohort group during these years. All other panels in this cohort are assumed to reach EOL during their useful lifetime period. In summation, the following assumptions for modelling purposes are shown in Table 16, using 2018 as an example year.

Table 16. 2018 Assumptions for Solar PV Panel Cohort Losses

Stage of Loss	% of Initial Cohort Lost
First 15 Years after Installation (transportation losses, damages, breakages)	4%
15-25 Years after installation (damages, weather related breakages)	5%
Lost at useful life (25-35 years after installation)	91%
Total Loss	**100%**

Once the useful life of a solar PV panel is reached, panels are assumed to have an even decommissioning distribution over the period of the useful life. For example, in a group of 100 panels which have reached their useful life of 25-35 years, 10 panels would be decommissioned every year from years 25 to 35.

It should be noted that in PV ICE documentation, the year at which failure rates for installed panels are 50% and 90% can be as high as 40 and 44 years, respectively.[36] This could indicate there is potential room for the useful lives of solar PV panels to be lengthened in this study. However, PV ICE applies these failure rates to solar installations which are installed in the years 2027 and beyond. Because this study focuses on the years 2025 to 2050, the solar PV panels which reach EOL after their useful lives will be installed prior to 2027. For this reason, Eunomia has assumed a slightly shorter and conservative useful lifetime of the solar PV panels than indicated by the PV ICE 50% and 90% failure rate timelines.

Table 17 shows the number of panels coming offline after conducting this approach. In total, an estimated 1.46 million panels will come offline in Minnesota between 2024 and 2050. The average annual number of panels coming offline increases in each subsequent time period. 14,000 panels come offline annually between 2024 and 2030, while 47,000 come offline annually between 2031-2040, and 336,000 panels come offline annually between 2041-2050.

Table 17. Estimated Number of Panels Coming Offline - 2024 to 2050

	Cumulative in Each Time Period				Average Annual in Each Time Period		
	2024-2030	**2031-2040**	**2041-2050**	**Total (2024-2050)**	**2024-2030**	**2031-2040**	**2041-2050**
Utility	70,000	215,000	1,181,000	**1,466,000**	7,000	21,500	118,100
Residential	10,000	38,000	262,000	**310,000**	1,000	3,800	26,200
Commercial	10,000	40,000	277,000	**328,000**	1,000	4,000	27,700
Industrial	20	260	420	**700**	0	30	40
Community Solar Garden	54,000	176,000	1,645,000	**1,875,000**	5,400	17,600	164,500
Total	**144,020**	**496,260**	**3,365,420**	**3,978,700**	**14,400**	**46,930**	**336,540**

Table 18 below shows the estimated number of panels reaching EOL each year for 2024 to 2050. For the overall installed base and sales market in 2024, including all grades of silicon panels and thin film cadmium-telluride panels, there are approximately 40 panels per ton, so the numbers in the utility, CSG, and total rows of this table can be multiplied by 25 to yield an approximate tonnage figure. For residential-commercial grade silicon panels only, there are 45 to 50 panels per ton (40-45 pounds per panel), so the numbers in the residential-commercial rows can be multiplied by 20 to 22 to yield an approximate tonnage figure. See Section 3.2.3.1 for additional discussion of panel weights and conversion factors.

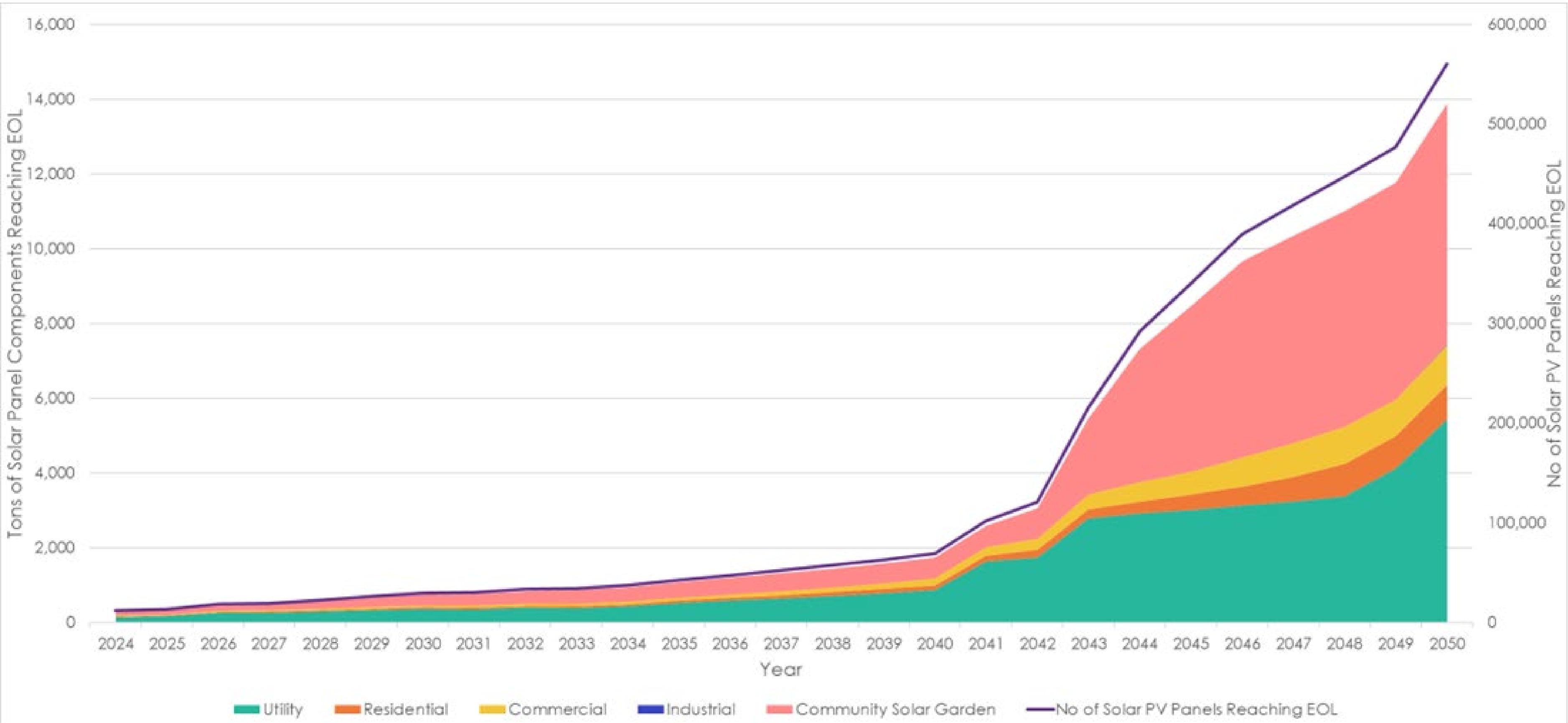
Table 18. Estimated Annual Number of Solar Panels Reaching EOL (1000 Panels)

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
Utility	5	7	10	10	11	13	14	13	15	14	16	20	22	25
Residential	1	1	1	1	1	2	2	2	3	3	3	3	4	4
Commercial	1	1	1	1	2	2	2	2	3	3	3	3	3	4
Industrial	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Community Solar Garden	5	5	7	7	8	10	12	13	13	14	16	17	18	20
Total	12	13	19	20	23	26	30	31	33	35	38	43	48	52

	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	
Utility	27	30	33	62	66	105	110	113	118	121	127	155	205	
Residential	5	5	6	8	10	13	16	21	26	34	44	44	47	
Commercial	5	6	7	9	13	16	21	25	32	37	41	40	44	
Industrial	0	0	0	0	0	0	0	0	0	0	0	0	0	
Community Solar Garden	21	22	23	23	33	83	145	181	214	227	236	237	265	
Total	58	63	70	102	121	216	292	340	390	419	448	477	561	

Figure 34 shows the results from transforming this forecasting approach from panels into tonnage. Annual EOL solar PV panels begin to rise in greater numbers after 2040. Community solar garden panels make up the majority of tons of solar PV panels reaching EOL. At their peak in 2050, just under 14,000 tons of solar PV panels reach end of life each year.

Figure 34. Projected Tons of Solar PV Panels Reaching End of Life



3.2.4 Recycling Yields

Eunomia used the following recycling yields to estimate the yield of capturing material from solar panels in the modelling. Recycling yields were sourced from Cui et al.[37] See Section 3.3.6 for the levels of recycling/recovery assumed for each type of installation in each scenario and overall material recovery from dismantling/recycling processes.

Table 19. Assumed Recycling Yields of Silicon Solar Panels

Material	Limited Recycling Process (Glass Recovery Focused) Recovery Rate	Comprehensive Recycling Process Recovery Rate
Glass	98%	98%
Copper	0%	83%
Silicon	0%	97%
Aluminum	94%	99%
Silver	0%	74%
Estimated overall yield	**80%**	**91.9%**

3.3 Policy Scenario Modelling

This section will lay out the modelling exercise performed to compare different EOL policies for solar PV panels. Eunomia conducted a cost benefit analysis of five policy scenarios, as well as a no new policy (i.e., do nothing) scenario. The costs and benefits included in this analysis include the value and cost of managing the material in solar panels. They do not include revenue streams which occur during the lifetime of the panel such as the value of the electricity generated. The benefits to owners or utilities specifically could be greater when factoring in the value of electricity generated from the solar panels. Furthermore, reuse can increase the economic value of solar panels during their lifetime, however for this analysis the benefits of reusing solar PV panels are mainly concerned with the panel reaching its end of useful life. Future analysis should further consider the benefits of solar PV panel reuse.

In some scenarios, different policies were applied to different sectors per stakeholder feedback. Each scenario was developed to produce an assumed 100% collection rate of EOL solar PV panels, as mandated by Minnesota Session Laws Chapter 60, Article 3, Section 36. Each scenario is summarized in Table 20.

Table 20. Overview of Scenarios Modelled

	No New Policy	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Short Description	**No policy except existing decommissioning (>50MW)**	**Lower Decomm threshold w/recycling requirement (e.g. >1MW); Disposal ban for all**	**Lower Decomm threshold w/recycling reqmt; Disposal ban for all; recycling targets <1MW**	**Permittee/Owner pays; Decomm reqmts >1MW, Disposal ban and recycling requirements for all**	**Full EPR to manage all panels; Decomm reqmts >1MW; Disposal ban and recycling requirements for all**	**Decomm/recycle reqmts for utility only, EPR for all other installations; disposal ban for all**
By Sector						
Utility	Decommissioning (>50MW)	Decommissioning/ recycling >1MW; Disposal ban	Decommissioning/ recycling >1MW	Decommissioning/ recycling >1MW	Full EPR and Decommissioning (All Capacity)	Decommission/ recycling >1MW
Residential	No New Policy	Disposal ban	Landfill Ban with Targets	Permittee	EPR	EPR
Commercial	No New Policy	Disposal ban	Landfill Ban with Targets	Permittee	EPR	EPR
Industrial	Decommissioning (>50MW)	Decommissioning/ recycling >1MW		Decommissioning/ recycling >1MW; Permittee	EPR	EPR
Community Solar Garden	No New Policy	Disposal ban Decommissioning/ recycling >1MW	Decommissioning/ recycling >1MW Landfill Ban with Targets	Decommissioning/ recycling >1MW; Permittee	EPR	EPR

3.3.1 Scenario Assumptions

Underlying each scenario is a set of key scenario design assumptions, summarized in Table 21 below. These assumptions show the different mechanics by which EOL solar PV panels are collected and what happens to them post-collections in each scenario. While the scenarios described in Table 20 show the policies which govern each scenario, it is the design assumptions in Table 21 that are the drivers for how the policies impact cost and recycling.

Table 21. Key Assumptions made for Scenarios Modelled

	No New Policy	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Description	**No policy except existing decommissioning (>50MW)**	**Lower Decomm threshold w/recycling requirement (e.g. >1MW); Disposal ban for all**	**Lower Decomm threshold w/recycling reqmt; Disposal ban for all; recycling targets <1MW**	**Permittee/ Owner pays; Decomm reqmts >1MW, Disposal ban and recycling requirements for all**	**Full EPR to manage all panels; Decomm reqmts >1MW; Disposal ban and recycling requirements for all**	**Decomm/recycle reqmts for utility only, EPR for all other installations; disposal ban for all**
Large Volume Collection	Bulk pickup	Bulk pickup	Bulk pickup	Bulk pickup	Bulk pickup	Bulk pickup
Small Volume Collection	None	Public or Private Depots	Public or Private Depots	Dedicated (modelled at one per county)	Dedicated (modelled at one per county)	Dedicated (modelled at one per county)
Transportation – Large Volume	Direct to Recycler	Direct to Recycler	Direct to Recycler	Direct to Recycler	Direct to Recycler	Direct to Recycler
Transportation – Small Volume	None	Bulking Center then recycler	Bulking Center then recycler	Bulking Center then recycler	Bulking Center then recycler	Bulking Center then recycler
Recycler Location – Large Volume Sites	Out of state for large	Out of state	Out of state	Out of state	Out of state until enough volume for Minnesota	Out of state until enough volume for Minnesota
Recycler Location – Small Volume Sites	Minnesota	Minnesota	Minnesota	Minnesota	Minnesota	Minnesota
Level of Recycling	Limited*	Limited for panels above threshold, hazardous disposal for others	Comprehensive** for all but utility sector	Modeled with: limited for all; and comprehensive for all	Comprehensive for all	Comprehensive for all but utility sector
Program Management	N	N	N	Y	Y	Y

*Limited recycling refers to glass and aluminum recovery only and is at a 98% glass recovery yield,[38] aluminum is also recovered however no other materials are recovered. The average overall yield is 80%.
**Comprehensive recycling refers to comprehensive recovery of all materials and averages at a 91.90% yield.[39]

The designation between scenarios with limited and comprehensive recycling is related to which scenarios best represent the current situation with weight-based targets in the EU, where facilities recover glass and metals only and are not meeting legislated targets.[40] Without additional stipulations within legislation, such as specific recycling targets common under EPR, the model assumes a limited recycling process. This is discussed further in Section 2.2. This section shows the total costs as well as the costs per panel. A full comparison of cost per panel for each step can be seen in Table 44 of Section 4.0

3.3.2 Deinstallation Costs

Eunomia has estimated de-installation costs based on per panel costs received from two solar installers from a survey sent out to MnSEIA members as part of this study (see Appendix A.1.0). The two responses from that survey provided the estimates shown in Table 22.

Table 22. Solar Installer Survey Responses

Survey Respondent	Cost to Uninstall Panels
Installer 1	$500-$1000 per panel for one off, $50 per panel for bulk
Installer 2	$100 per panel

Using these estimates, Eunomia calculated weighted average costs to deinstall solar PV panels in bulk and individual settings. These costs are shown below in Table 23.

Table 23. Average Cost to Deinstall Solar PV Panels

Panel Type	Average Cost per Panel to De-install
Cost per Panel - Bulk	$75
Cost per Panel - Individual	$300

The following assumptions shown in Table 24 regarding what percent of solar PV panels would be deinstalled in bulk and what percent would be deinstalled individually were made for each installation type:

Table 24. Percent of Solar PV Panels to be Deinstalled in Bulk and Individually for each Installation Type

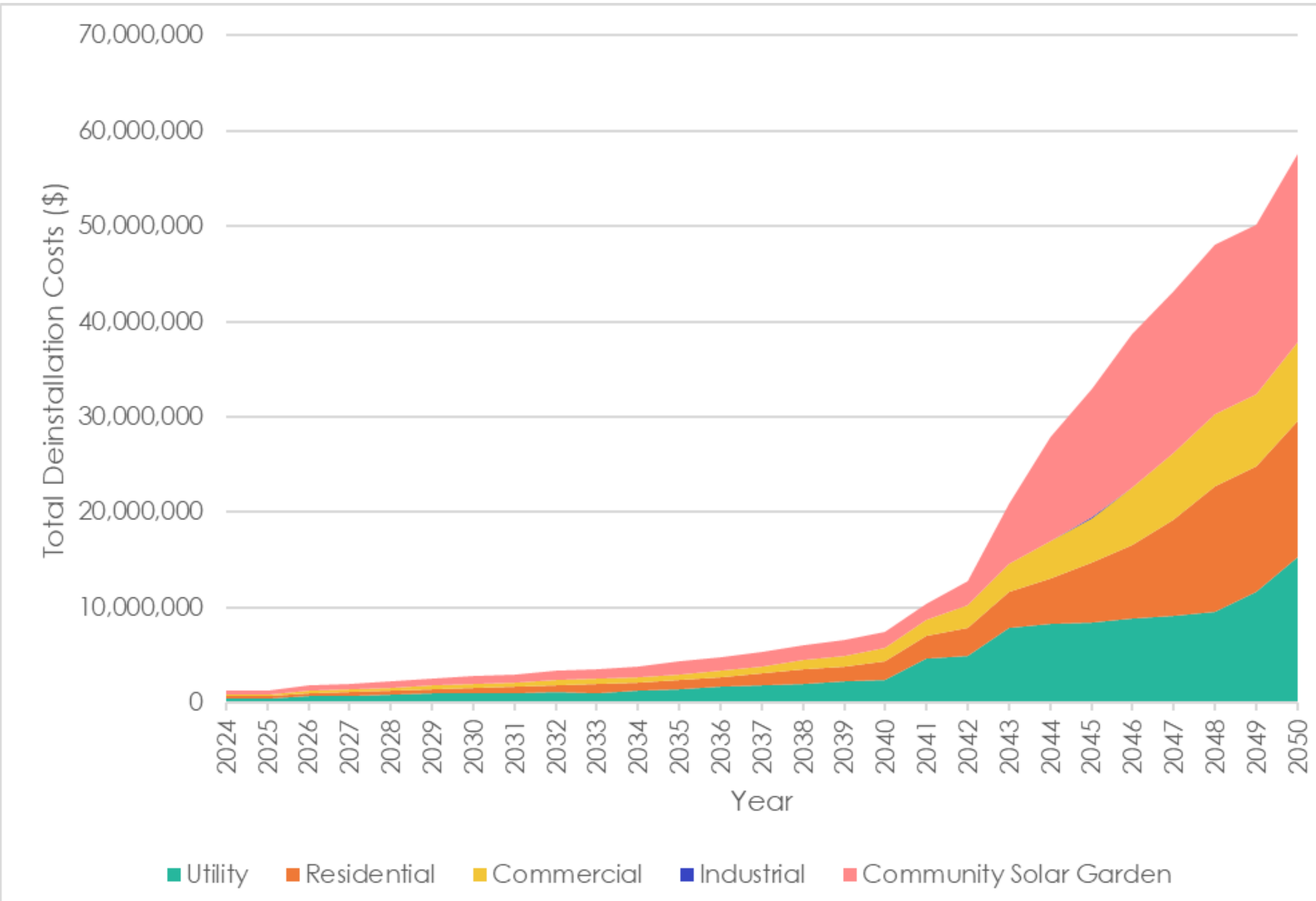
	% deinstallation in bulk	% deinstallation small scale
Utility	100%	0%
Residential	0%	100%
Commercial	50%	50%
Industrial	75%	25%
Community Solar Garden	100%	0%

Total deinstallation costs were calculated by multiplying the total number of solar PV panels reaching EOL in each given year, by the cost to uninstall panels in bulk and/or individually based on the above percents.

Deinstallation costs are not included in the total system cost under each scenario. This is because the de-installation costs will occur regardless of whether the panels are destined for landfill or recycling.

Figure 35 shows the total deinstallation costs for each installation type from 2024 to 2050. In 2050, at their peak, deinstallations costs reach over $57 million, with community solar garden installations making up ~$19.8 million of this total cost. This is because the highest number of solar PV panels are coming offline in 2050. Note that this cost of $ per panel dwarfs the costs of reuse/recycling in the high performing Scenarios 3b through 5, $19 to $22 per panel in 2050.

Figure 35. Total Deinstallation Costs for End-of-Life Solar PV Panels

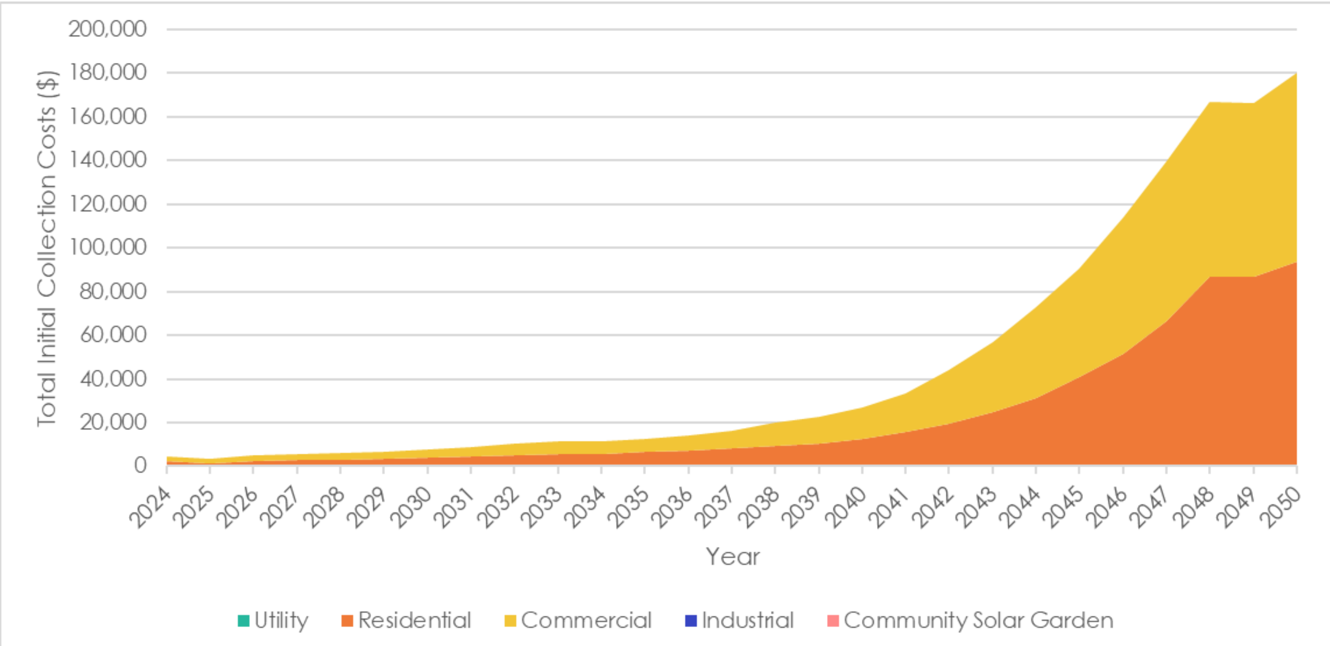


3.3.3 Initial Collection Costs

Initial collection costs refer to the cost of transporting the uninstalled EOL solar PV panels to a consolidation center. Eunomia assumed that residential and commercial installations would initially be brought to a consolidation center and utility, industrial, and community solar garden installations would be brought directly to a recycling center. Initial collection costs only factor in costs associated with bringing EOL solar PV panels to consolidation centers, therefore only residential and commercial solar installation types have initial collection costs. Figure 36 shows the total initial collection costs for both commercial and residential installation types. In 2050, these costs are at their highest, totaling ~ $180,000

Initial collection costs are assumed to occur under each scenario, as each scenario shows the cost of collecting 100% of solar panels in the state. While the funder for these costs will not be the same under each scenario, the cost is still shown to compare the total cost of Scenario 1 (no residential or commercial recycling) to the subsequent scenarios where recycling is implemented. Note that in Scenario 1, there is no incentive for the panels to be recycled.

Figure 36. Total Initial Collection Costs for all EOL Solar PV Panels



Full costs per panel and by sector type for initial collection across all scenarios are shown in Section 3.4.

3.3.4 Consolidation Costs

Consolidation costs refer to the costs to receive and store solar PV panels at consolidation centers. Consolidation centers can either be public or private dedicated sites. Depending on the scenario, the following assumptions were made:

- For all scenarios, Eunomia assumed that 100 percent of utility type solar installations which have reached their end of useful life would go directly to a recycling center.
- In the No New Policy Scenario, Scenario 1, Lower Decommissioning Threshold, and Scenario 2, Landfill Ban with Targets, Eunomia assumed that 100 percent of residential and commercial installations would go to public sites and 100 percent of industrial and community solar garden installations would go to dedicated collection facilities.
- In Scenario 3, Permittee with Limited Recycling Process, Scenario 4 Full EPR, and Scenario 5, Decommissioning for Utility, EPR for all other, Eunomia assumed that 100 percent of residential, commercial, industrial, and community solar garden installations would go to dedicated facilities.

Eunomia used the following costs, stated in Table 25, regarding the cost of receiving and storing solar PV panels in sites collecting other materials versus dedicated solar panel sites, provided by a solar installation company employee:

Table 25. Cost of Receiving and Storing Solar PV Panels in Public and Private Sites

Site Type	Cost to Handle Each Panel
Site Co-Collects Other Material	$6.00/panel
Private Site	$1.00/panel

Source: Interview with PV Cycle

These costs to sort and store solar PV panels are 6.0x more in co-collection sites compared to dedicated sites, as they are less equipped to handle EOL solar PV panels and more sorting is involved. In the modelling, Eunomia assumes that this difference will shrink by the time the program matures in 2040, reducing co-collection costs from $6 per panel to $2.5 per panel. These co-collection costs are only seen in Scenarios 1 and 2, while Scenarios 3-5 have private site costs.

Figure 37 and Figure 38 show these costs for each scenario. There are no costs associated with receiving and storing solar PV panels in the No New Policy Scenario. The costs in Scenario 1 (Lower Decommissioning Threshold), and Scenario 2 Landfill Ban with Targets) reach almost $300,000 in 2050 at their peak (shown in Figure 37), while the costs in Scenario 3 (Permittee with Limited Recycling Process), Scenario 4 (Full EPR), and Scenario 5 (Decommissioning for Utility, EPR for Other) only reach almost $180,000 at their peak in 2050 (shown in Figure 38). Scenarios 3-5 have a lower overall cost as they are assumed to have the private site cost of $1.00/panel, while Scenarios 1-2 have the optimized co-collection cost of $2.5/panel.

Figure 37. Costs to Receive and Store Solar PV Panels at Consolidation Centers – Scenario 1, and Scenario 2

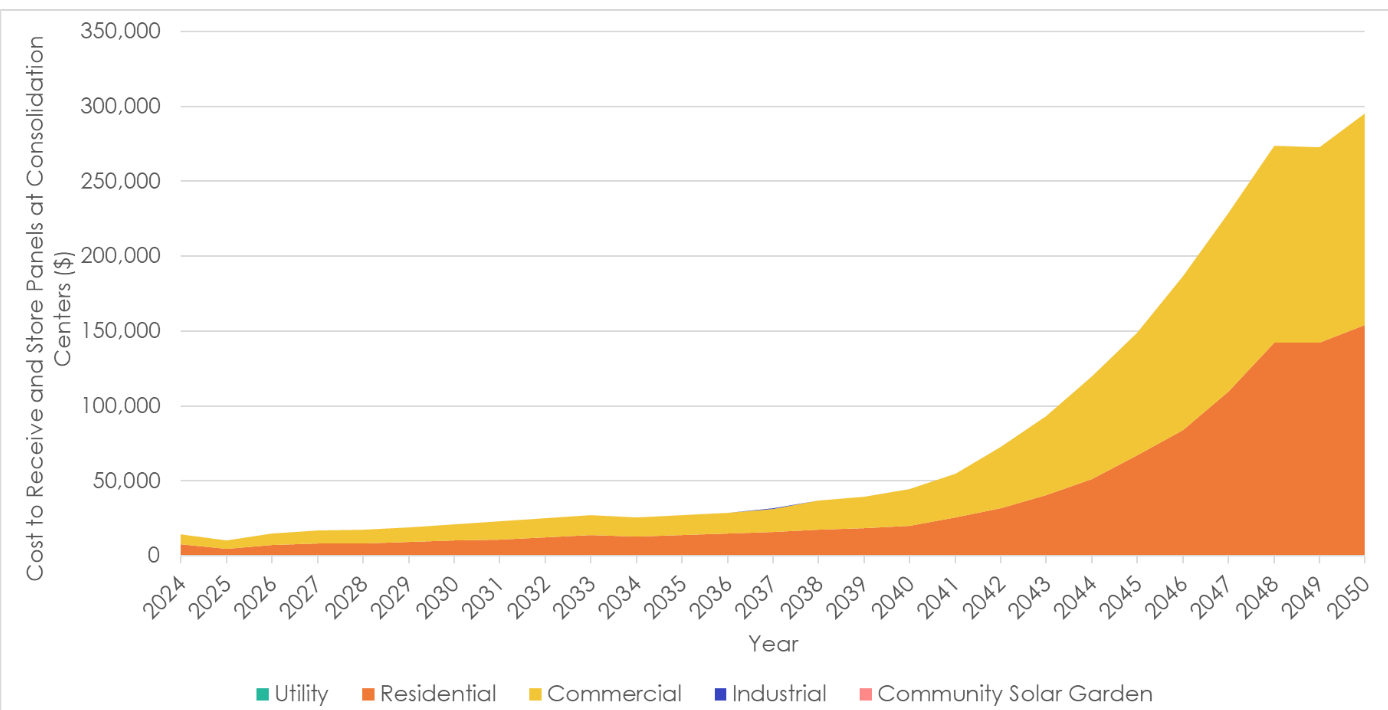
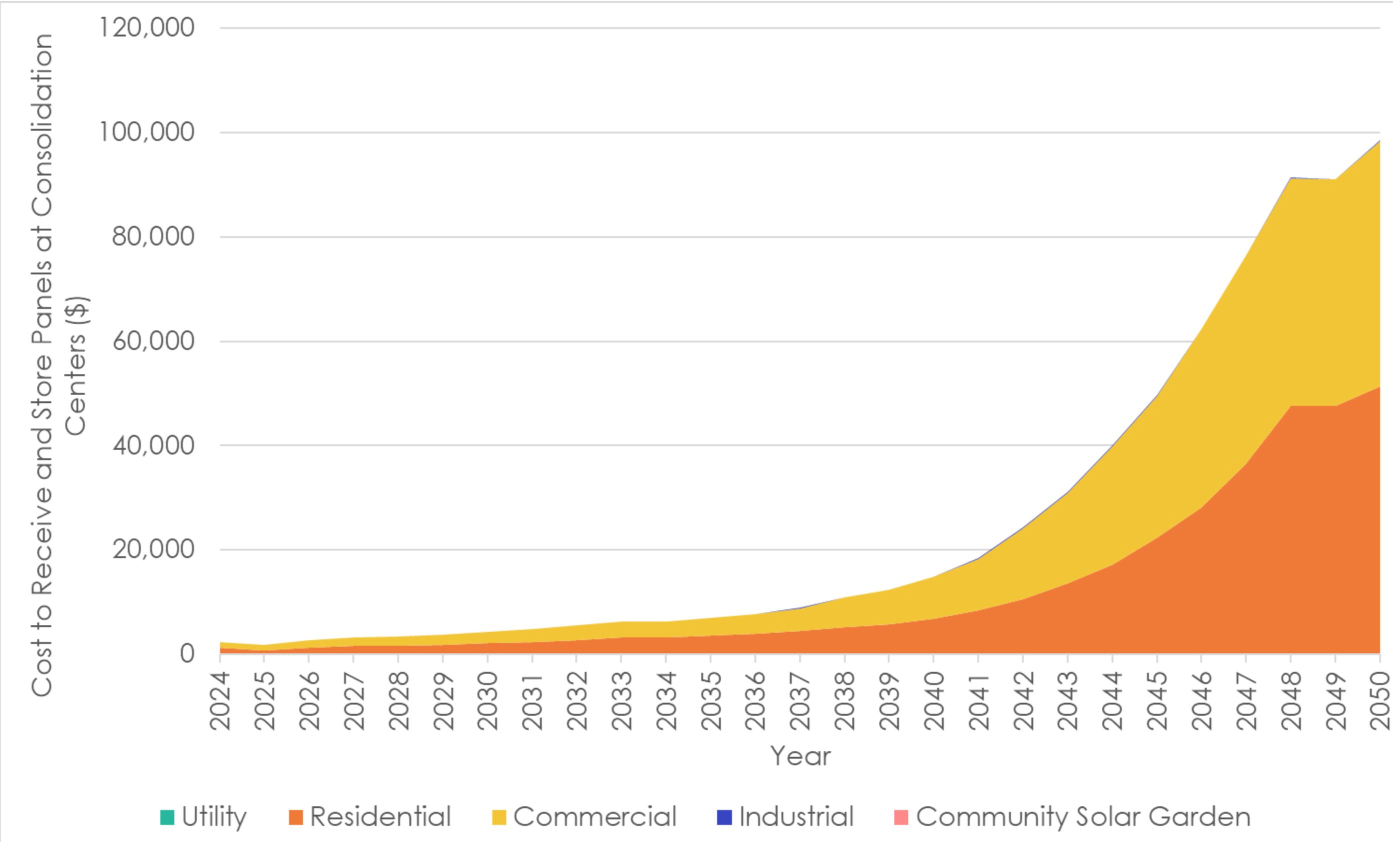


Figure 38. Costs to Receive and Store Solar PV Panels at Consolidation Centers – Scenario 3, Scenario 4, and Scenario 5



Full cost per panel results for consolidation center costs can be found in Section 3.4.

3.3.5 Transportation Costs

Transportation costs refer to the costs associated with transporting the EOL solar PV panels to their place of recycling. For Scenario's 1, 2 and 3, Eunomia assumed that the recycler location would be in Ohio, as this is currently where the nearest solar PV panel recycler is located. For Scenario's 4 and 5, Eunomia assumed that the recycler location would be in Ohio, until there was a large enough volume of solar PV panels coming offline (<15,000 tons/year), to set up a recycling plant in Minnesota. This assumption does not affect the transportation cost results since there was no year modelled where greater than 15,000 tons of solar PV panels were expected to be coming offline.

Transportation costs were calculated by deriving a cost per panel per mile based on the following assumptions:

- A 53-foot truck can fit 420 solar PV panels.[41]
- The Midwest flatbed rate is $2.55/mile.[42]

Dividing the number of panels in the truck by the cost per mile would suggest a cost of 0.006 cents per panel per mile. The total miles the EOL solar PV panels would have to travel to reach the recycling location was then calculated, using Geographic Information System (GIS) analysis on the distance to either a regional recycler or the out of state recycler. The average distance for panels to travel to one of the 5 assumed regional versus out of state recyclers are shown below. The average distance is weighted by population:

Table 26. Average Distances by Recycler Location

Recycler Location	Average Distance to Recycler of Minnesota Solar PV Panel (miles)
To Regional Recycler (in-state)	30
Out of State	700

Eunomia assumed that half of the journeys to the recycler location would require a return journey which is why the total miles calculated by GIS was multiplied by the cost per panel per mile and by 1.50 journeys to the recycling location. This gave us the transportation cost per panel which was then multiplied by the number of panels expected to reach EOL in each given year to give the total transportation costs.

Figure 39. Costs to transport EOL Solar PV Panels to Recycler – No New Policy Scenario

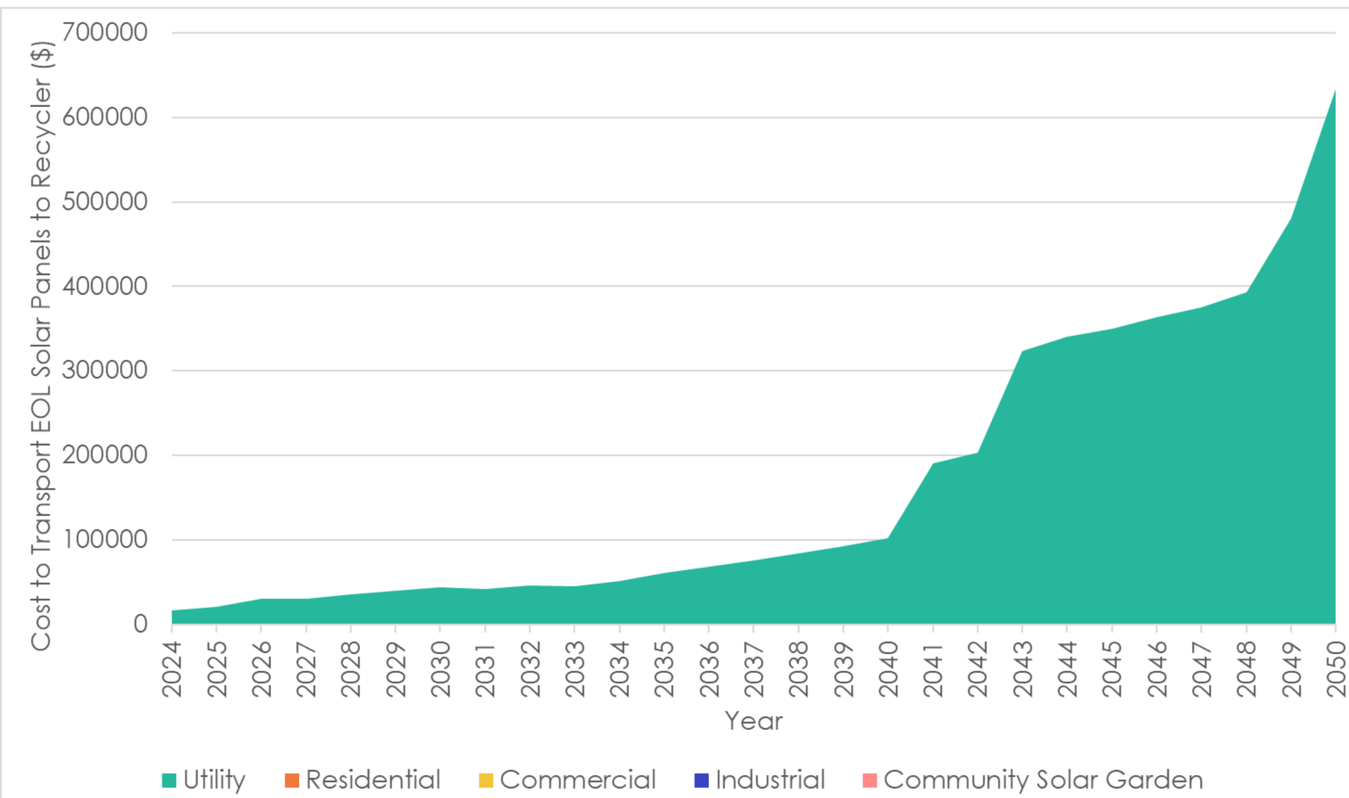
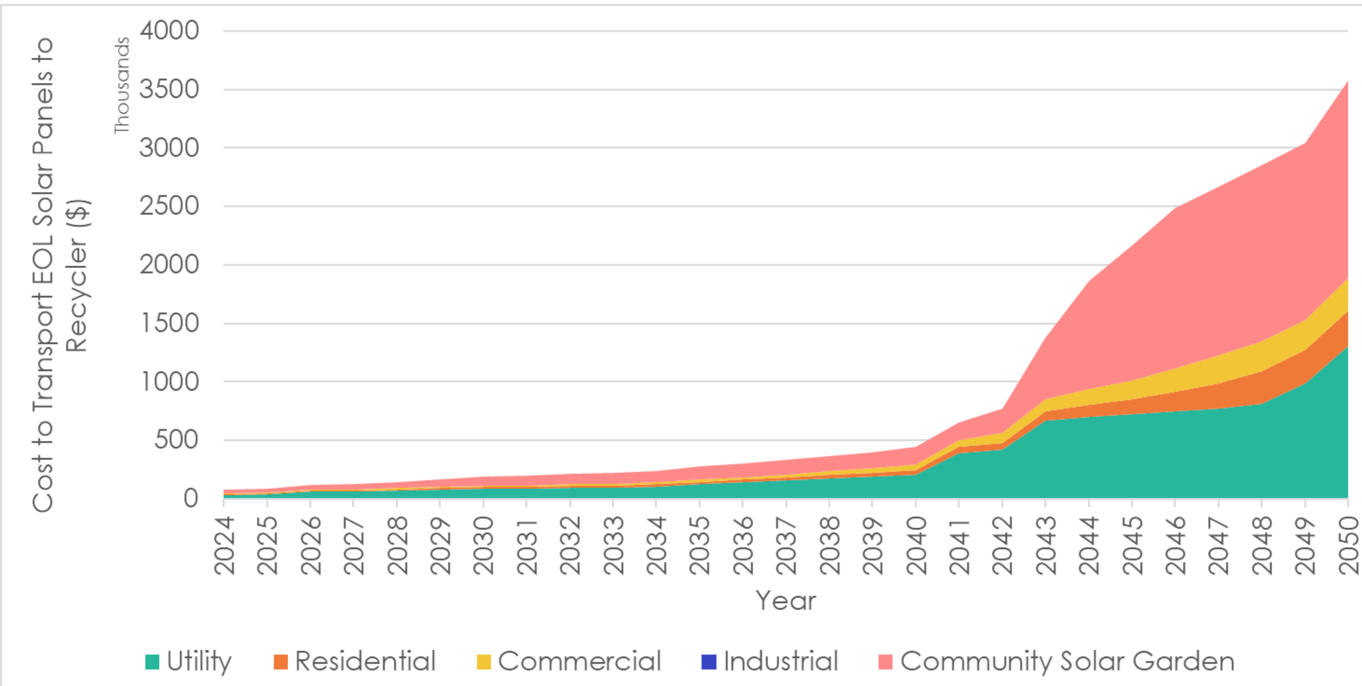


Figure 39 shows the costs associated with transporting EOL solar PV panels to their recycling location for the No New Policy Scenario. As this scenario requires no recycling, only utility solar installations have transportation costs. This is because Minnesota already requires utility scale solar installations that are >50MW to be decommissioned and brought to recycling centers. At their peak, in 2050, these costs reach ~$630,000.

Figure 40 shows the costs associated with transporting EOL solar PV panels to their recycling location for all other scenarios. All other scenarios have the same transportation costs because in each scenario Eunomia assumed that all solar PV panels would be brought to Ohio for recycling. At their peak, in 2050, these costs reach ~$2.9 million.

- CSG and Utility sectors account for 82% of the panels reaching EOL
- These panels are assumed to be shipped out of state, resulting in higher transportation costs

Figure 40. Cost to transport EOL Solar PV Panels to Recycler – Scenario 1, Scenario 2, Scenario 3, Scenario 4, and Scenario 5



Full transportation costs per panel and by sector can be found in Section 3.4.

3.3.6 Dismantling Costs

Dismantling costs refer to the costs associated with breaking down the EOL solar PV panels into their separate components. Eunomia assumed three levels of dismantling at recycling centers. Comprehensive recovery, limited recovery, and no recovery (WtE/landfill) and each of the five scenarios was given a different level of recovery for each solar PV panel installation type.

- No recovery was assumed for the No New Policy Scenario, except for utility scale solar installations for which limited recovery is already being done in Minnesota.

- In Scenario 1, Lower Decommissioning Threshold with Recycling Requirements, limited recovery was assumed for panels from all installations over the threshold of 1 MW DC.

- Comprehensive recovery was assumed for Scenario 2 (Landfill ban with Targets) except for utility installations, with limited recovery.

- Scenario 3 (Permittee Pays) had two permutations. Limited recovery was assumed for scenario 3a, with comprehensive recycling assumed for scenario 3b.
- Scenario 4 (Full EPR) assumes comprehensive recycling for panels from all installations.
- Limited recovery was assumed for all utility scale installations in Scenario 5 (Decommissioning for Utility, EPR for all other), with comprehensive recovery being assumed for all other installations managed through EPR.

To calculate the total costs of dismantling all solar PV panels that reach EOL from 2024 to 2050, Eunomia had to break out the number of each type of solar PV panel that are expected to reach EOL in each year. Eunomia assumed that all projected EOL solar PV panels in Minnesota were a combination of cadmium based solar PV panels, silicon based solar PV panels or 'other' based solar PV panels. A report by the Fraunhofer Institute for Solar Energy Systems[43] detailed the solar PV panels market share by type which Eunomia used to project the type of solar PV panels that would be coming offline from 2024 to 2050. Table 27 shows these market shares.

Table 27. Solar PV Panel Market Share by Type

Solar PV Type	2000	2014	2020	2030
Cadmium	10%	8%	10%	10%
Silicon	90%	92%	90%	90%

The costs associated with each type of recovery, by solar PV panel type are shown in Table 28. These are the costs for the dismantling portion of recovery only, and do not include transportation or collection costs. These costs were assumed based on conversations with stakeholders. Important to note, landfilling and WtE of e-waste can have additional costs in terms of human health and environmental impact that are not factored into these costs. Section 4.5 provides additional detail on the potential health and environmental impacts stemming from EOL management of solar PV panels.

Table 28. Costs associated with Dismantling (Net $/panel)

Solar PV Type	No Recovery (WtE/Landfill)	Limited Recovery	Comprehensive Recovery (early year cost – 2024)	Comprehensive Recovery (2050)
Silicon	1.30	10	20	14
Cadmium	1.30	13	25	18

Figure 41 shows the total costs to dismantle EOL solar PV panels for all scenarios in 2024, 2030, 2040 and 2050. Costs are highest in 2050, as this is when the greatest amount of EOL solar PV panels are expected to be coming offline. Costs are highest for Scenario 4 (Full EPR) and 3b (Permittee with Comprehensive Recycling) in 2050, where they reach ~$8 million. This is followed closely by Scenario 2 (Landfill Ban with Targets) and Scenario 5 (Decommissioning for Utility, EPR for all other) which reach ~$6.5 million in 2050.

Figure 41. Costs to Dismantle EOL Solar PV Panels for all Scenarios

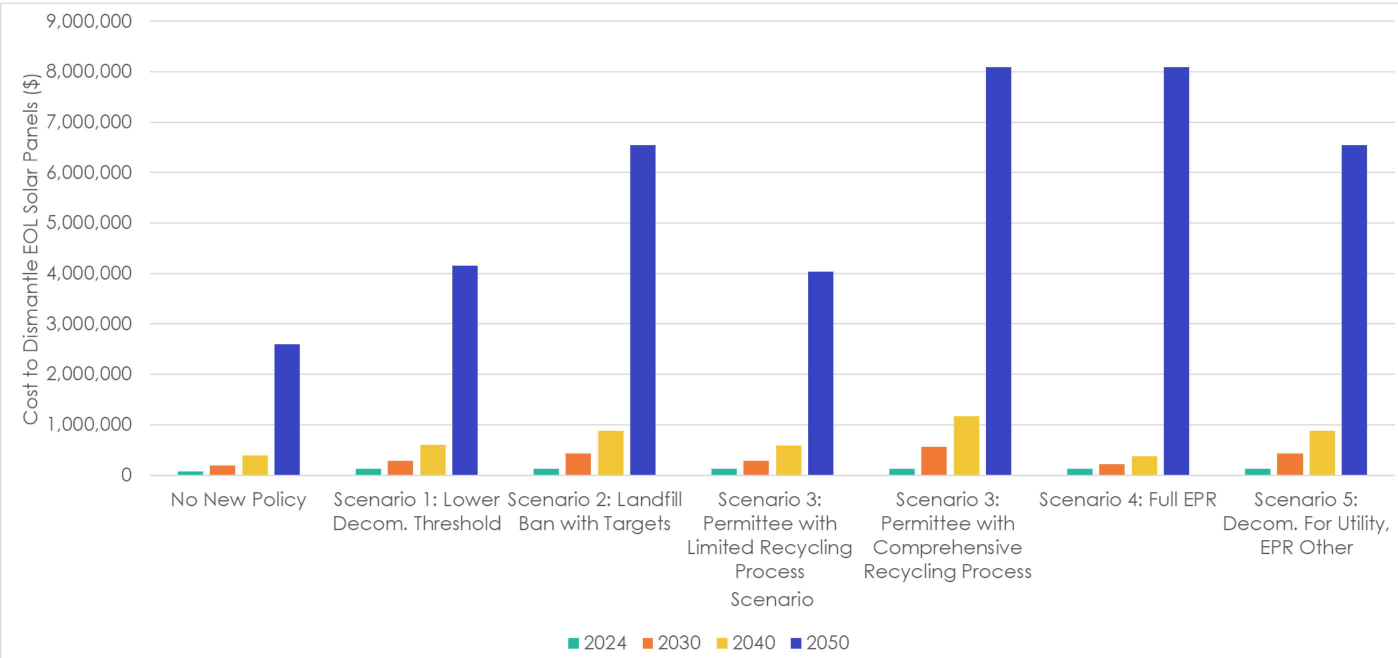


Figure 42 shows the total costs to dismantle EOL solar PV panels for all installation types from 2024 to 2050, for the No New Policy Scenario. These costs are the highest in 2050 reaching ~$3 million. Utility installations make up the greatest amount of these costs at ~$1.7 million in 2050, followed closely by Community Solar Garden installations which make up ~$690,000 in 2050. This is because Utility Installations >50MW already require limited recovery in Minnesota. There is an assumption that utilities currently engage in limited recycling.

Figure 42. Cost to dismantle EOL Solar PV Panels by Installation type – No New Policy Scenario

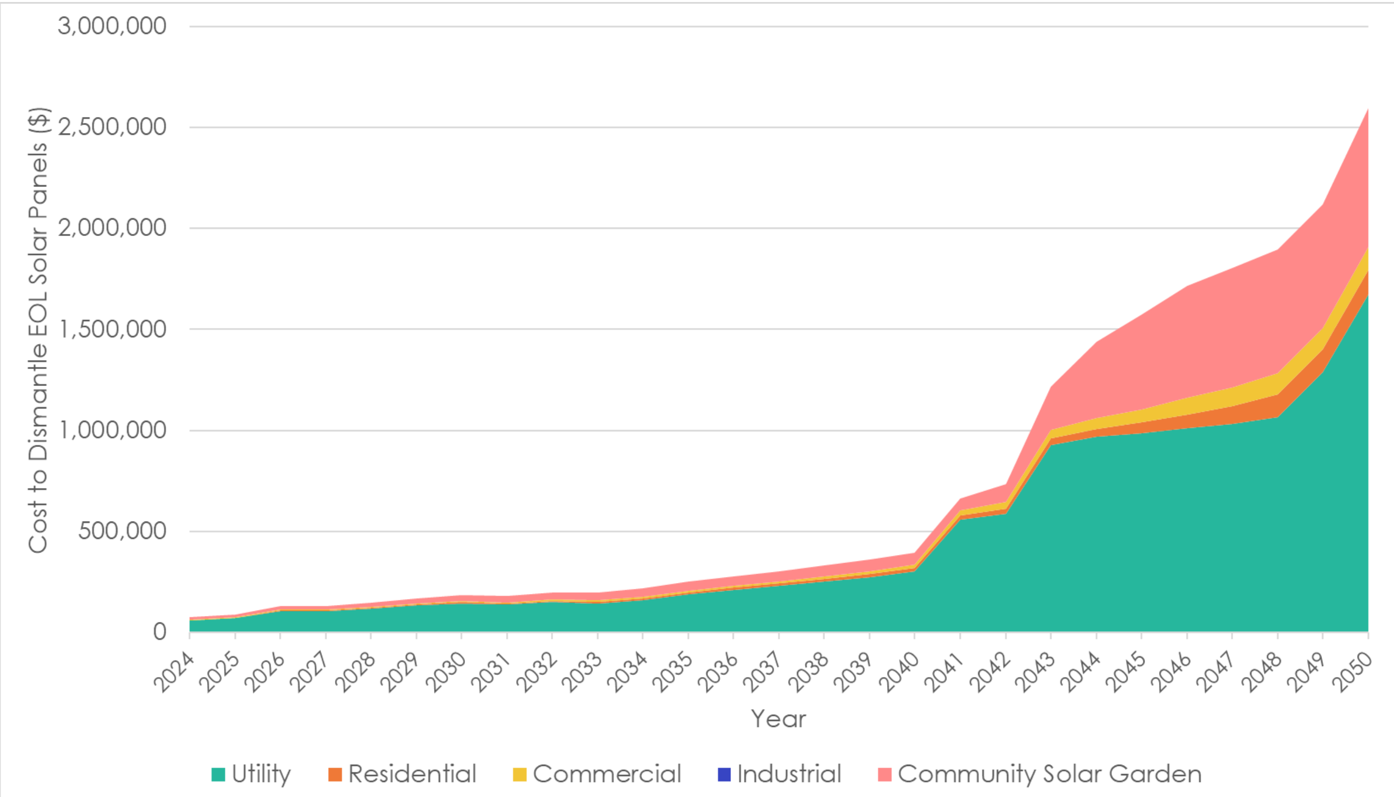


Figure 43 shows the total costs to dismantle EOL solar PV panels for all installation types from 2024 to 2050, for Scenario 1 (Lower Decommissioning Threshold [with disposal ban]). These costs are the highest in 2050 reaching ~$4.1 million. Community Solar Garden installations make up the greatest amount of these costs at ~$1.8 million in 2050, followed by Utility installations which make up ~$1.5 million. This is because Community Solar Garden installations making up the greatest amount of EOL solar PV panels in 2050. In this scenario, there is an assumption that panels below the threshold are properly disposed (e.g., sent to hazardous disposal).

Figure 43. Cost to Dismantle EOL Solar PV Panels by Installation Type – Scenario 1

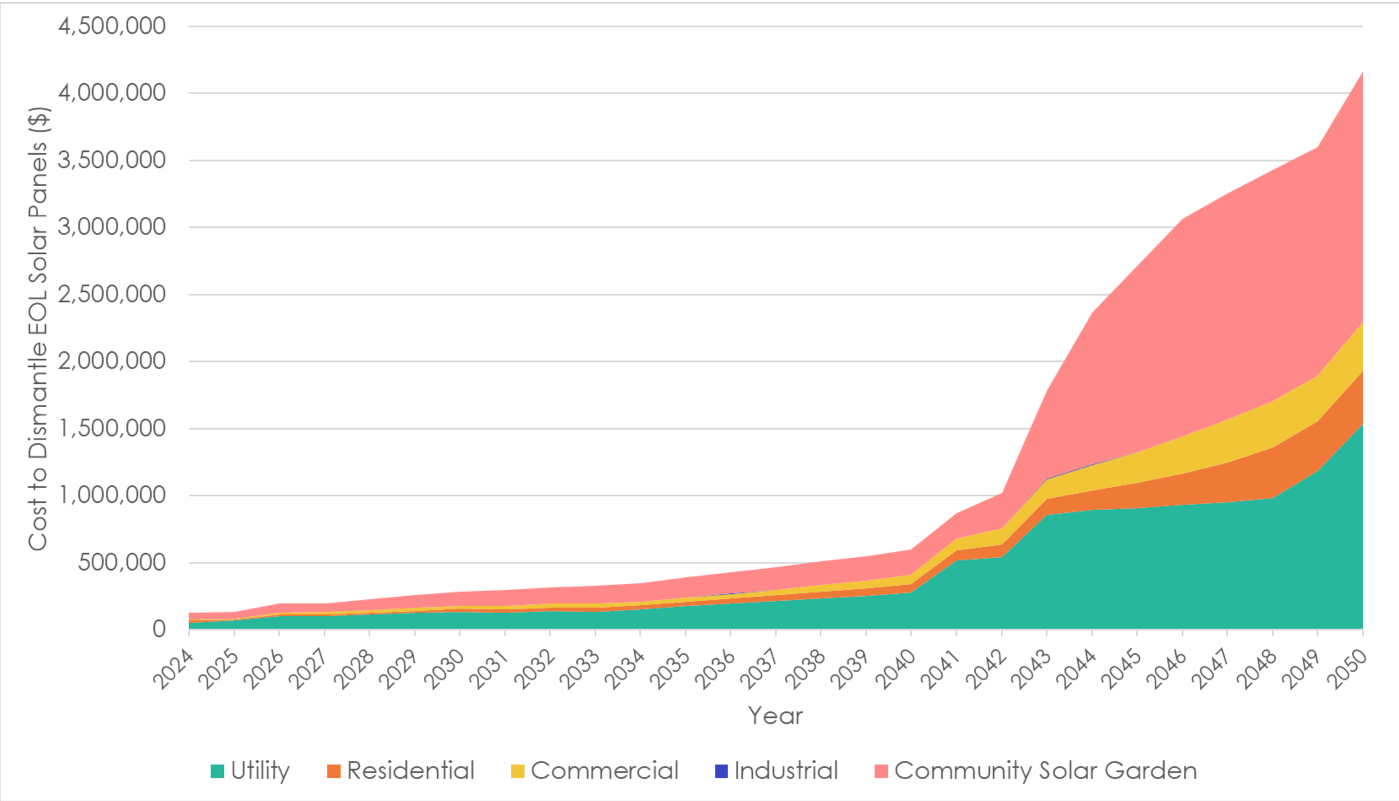


Figure 44 shows the total costs to dismantle EOL solar PV panels for all installation types from 2024 to 2050, for Scenario 2 (Landfill Ban with Targets). These costs are the highest in 2050 reaching ~$6.5 million. Community Solar Garden installations make up the greatest amount of these costs at ~$3.7 million in 2050, followed by Utility installations which make up ~$1.5 million [limited recycling] and Residential-commercial installations which make up ~$669,000 each ($1.3 million total) in 2050. This is because Community Solar Garden installations make up the greatest amount of EOL solar PV panels in 2050. Scenario 2 includes limited recycling for utility panels and comprehensive for all others.

Figure 44. Cost to Dismantle EOL Solar PV Panels by Installation Type – Scenario 2

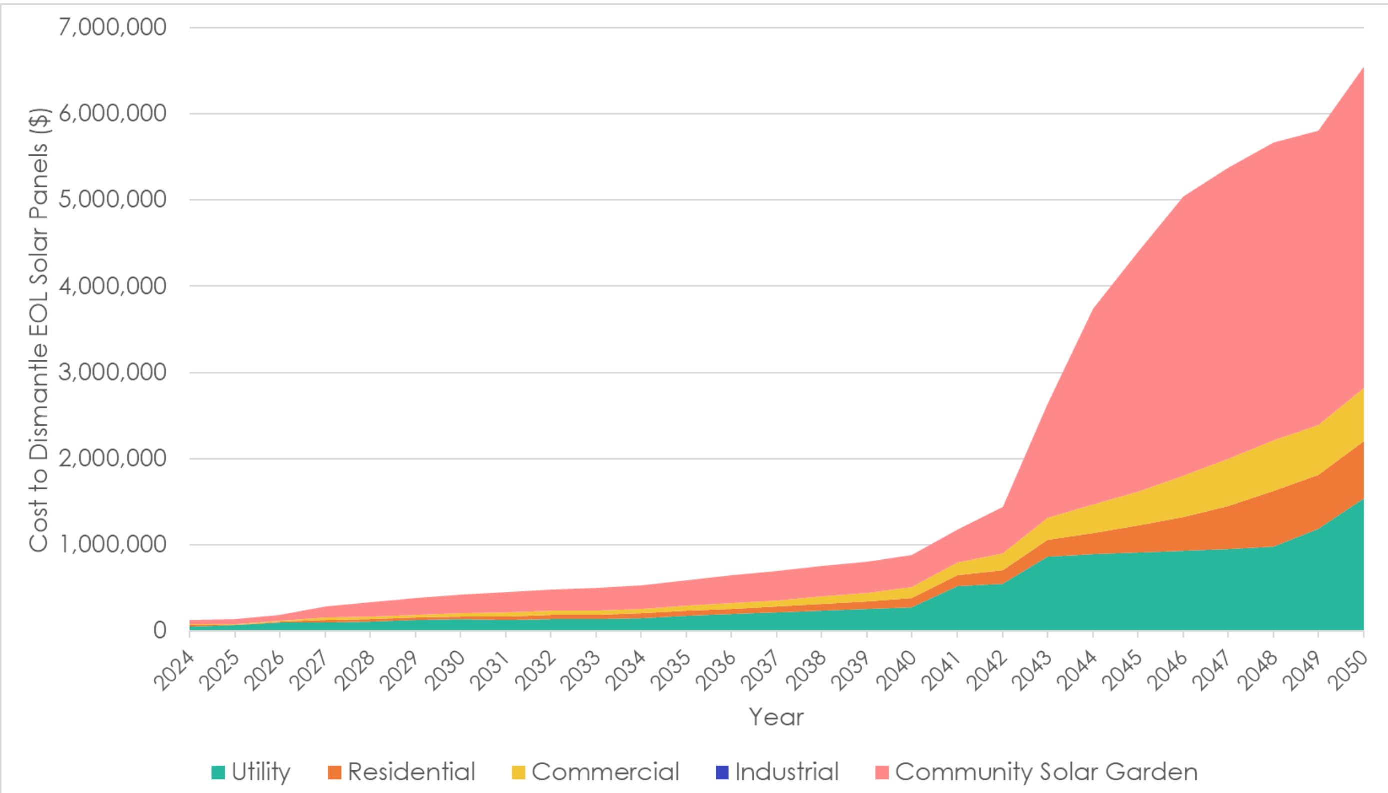


Figure 45 shows the total costs to dismantle EOL solar PV panels for all installation types from 2024 to 2050, for Scenario 3 (Permittee with Limited Recycling Process). These costs are the highest in 2050 reaching ~$4.0 million. Community Solar Garden installations make up the greatest amount of these costs at ~$1.9 million in 2050, followed by Utility installations which make up ~$1.5 million, and residential-commercial at $640,000 combined in 2050. Dismantling costs are much lower in this scenario, when compared to others, as only limited recycling is required.

When comprehensive recycling is used in this scenario instead of limited recycling (Scenario 3b), the total cost of dismantling increases to $8 million.

Figure 45. Cost to Dismantle EOL Solar PV Panels by Installation Type – Scenario 3a

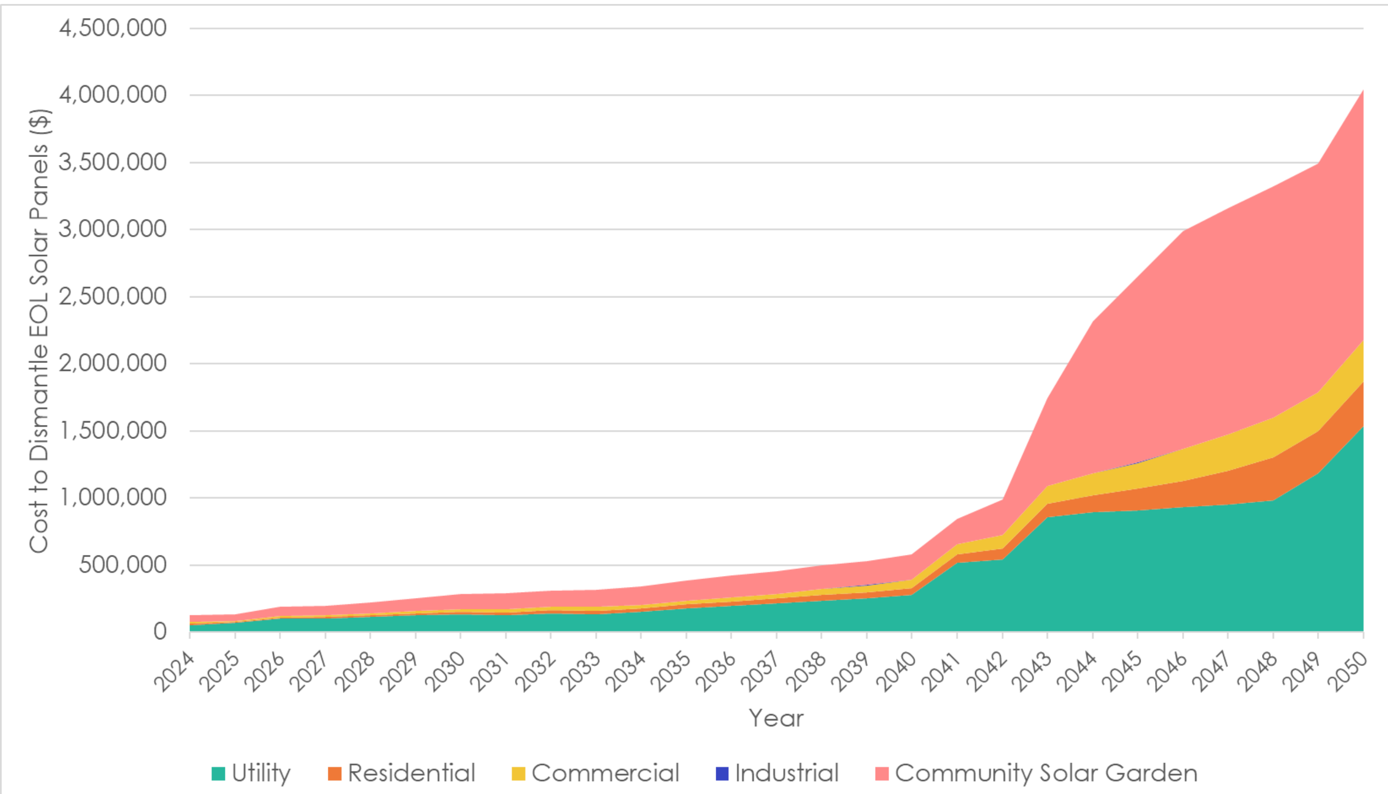


Figure 46 shows the total costs to dismantle EOL solar PV panels for all installation types from 2024 to 2050, for Scenario 4 (Full EPR). These costs are highest in 2050 reaching ~$8 million. Community Solar Garden installations make up the greatest amount of these costs at ~$3.7 million in 2050, followed by Utility installations which make up ~$3 million in 2050. Residential dismantling costs are $670,000, while commercial dismantling costs are $620,000. Dismantling costs are highest in this Scenario as comprehensive recycling is required for panels from all sectors.

Figure 46. Cost to Dismantle EOL Solar PV Panels by Installation Type – Scenario 4

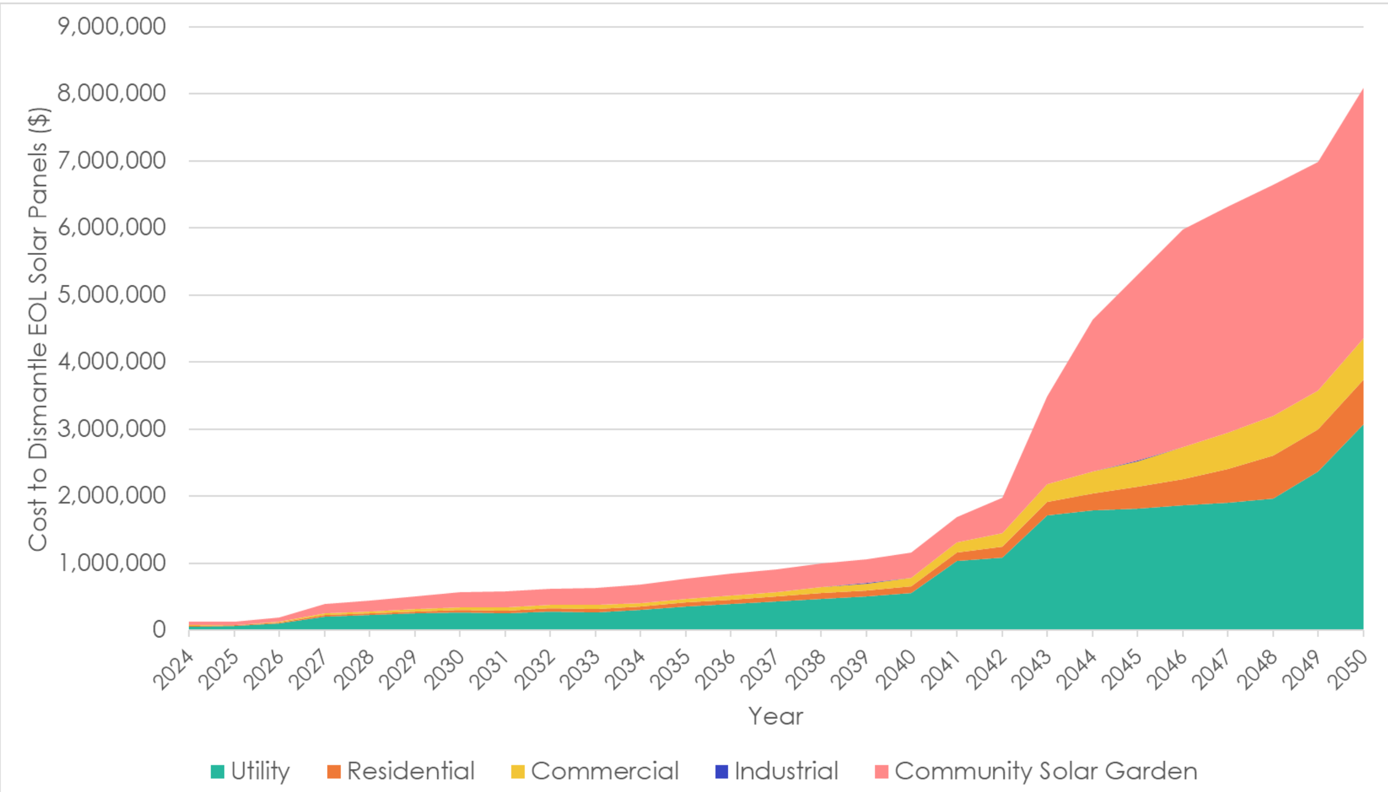
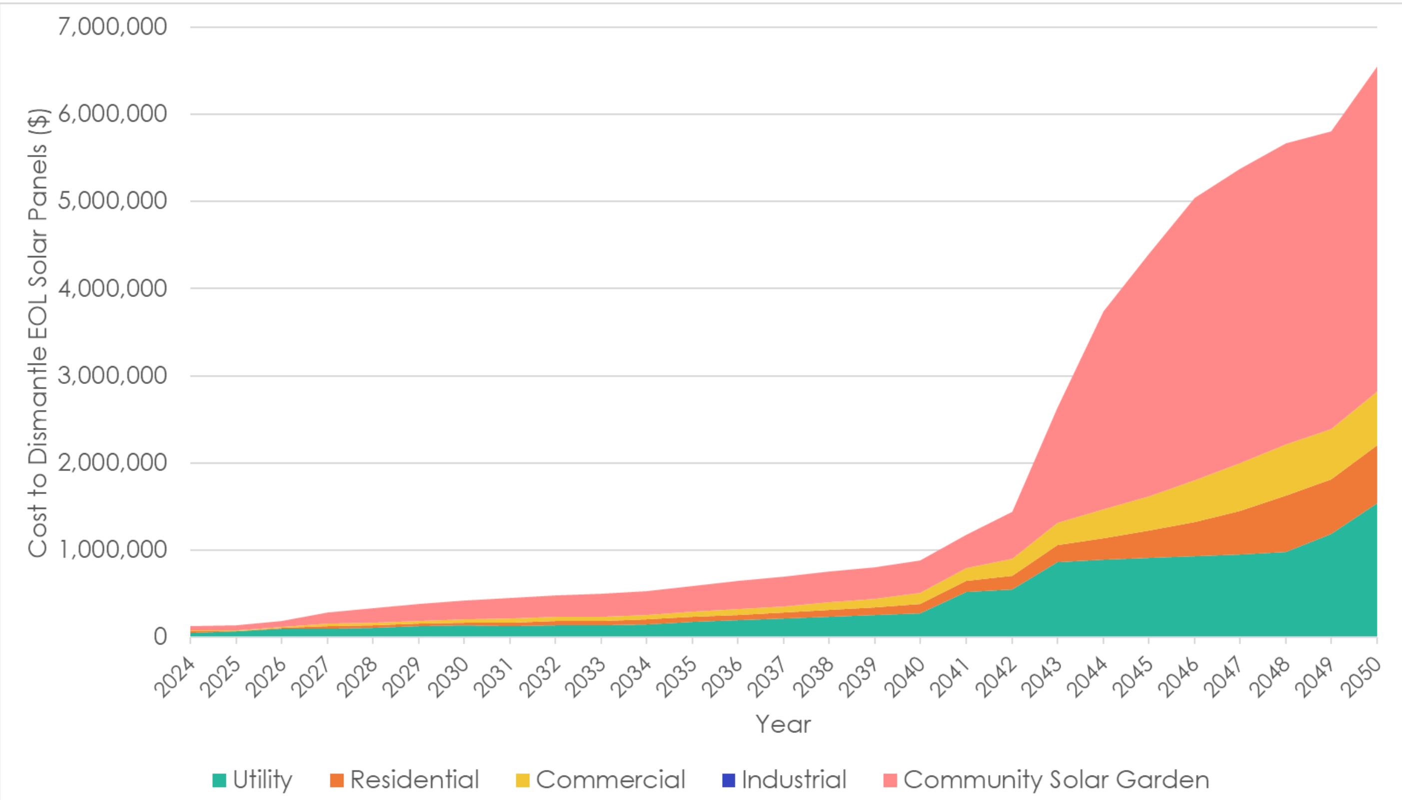


Figure 47 shows the total costs to dismantle EOL solar PV panels for all installation types from 2024 to 2050, for Scenario 5 (Decommissioning for Utility, EPR for all other). These costs are the highest in 2050 reaching ~$6.6 million. Community Solar Garden installations make up the greatest amount of these costs at ~$3.7 million in 2050, followed by Utility installations which make up ~$1.5 million in 2050. Residential and commercial again combine for just under $1.3 million in dismantling costs. In this Scenario utility panel recycling is limited and all others have comprehensive recycling.

Figure 47. Cost to Dismantle EOL Solar PV Panels by Installation Type – Scenario 5



Full dismantling and recycling costs by sector and per panel can be found in Section 3.4.

3.3.7 Program Management Costs, Overall and Per Panel

Program Management Costs refer to the costs associated with running an EOL solar PV panel recycling system. Eunomia assumed that program management costs would only be associated with Scenario 3 (Permittee Pays with Low Yield), Scenario 4 (Full EPR) and Scenario 5 (Decommissioning for Utility, EPR for all other), as these are the scenarios which introduce new policies. Eunomia calculated these costs based on a 2023 Annual Report from Soren, a French organization that specializes in the collection and recycling of solar PV panels and work to ensure compliance with French Solar PV EPR laws. Eunomia included operations and administrative costs, research and development costs, and communication costs under program management costs. Eunomia calculated these costs on a per capita basis and ensured that the program would have enough FTEs to provide function.

Figure 48 shows the total program management costs for Scenarios 3a (Permittee with limited recycling), Scenario 3b (Permittee with comprehensive recycling), Scenario 4 (Full EPR) and Scenario 5 (Decommissioning for Utility, EPR for all other). Eunomia included administration costs, research and development costs, and communication costs under program management costs for these scenarios. These costs range from ~$120,000 in 2024 to ~$127,000 in 2050. Administration costs make up the greatest proportion of these costs at ~$90,00 in 2050, followed by communication costs which make up ~$24,500 in 2050. Research and development costs make up ~$12,500 in 2050.

Figure 48. Total Program Management Costs – Scenarios 3a, 3b, 4, and 5

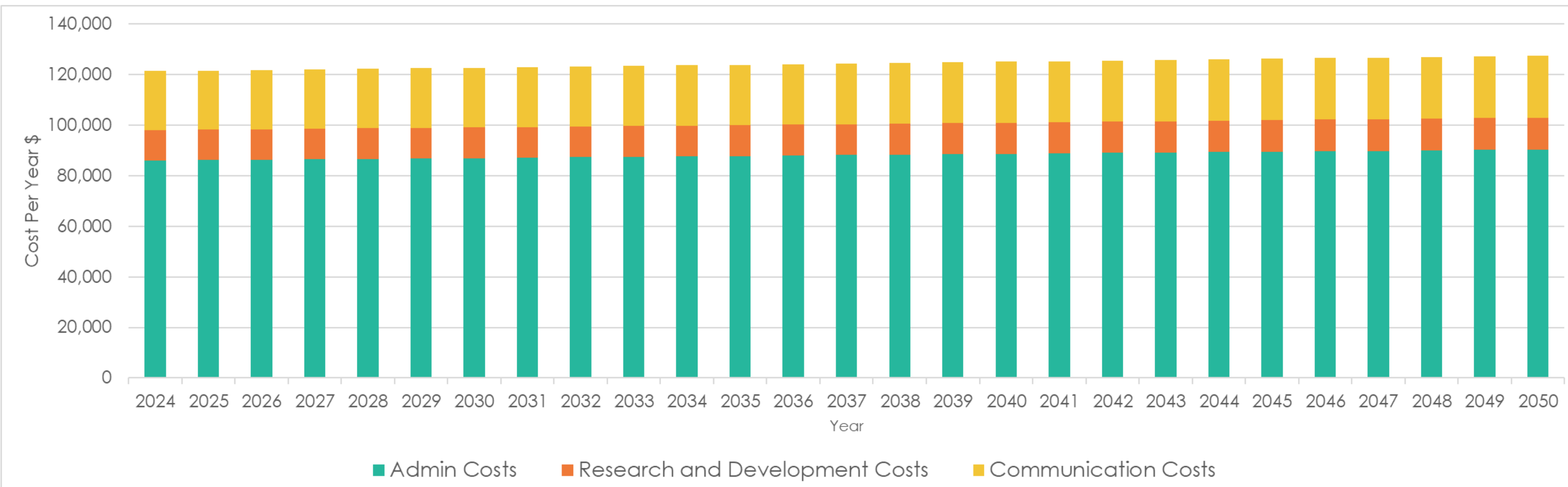
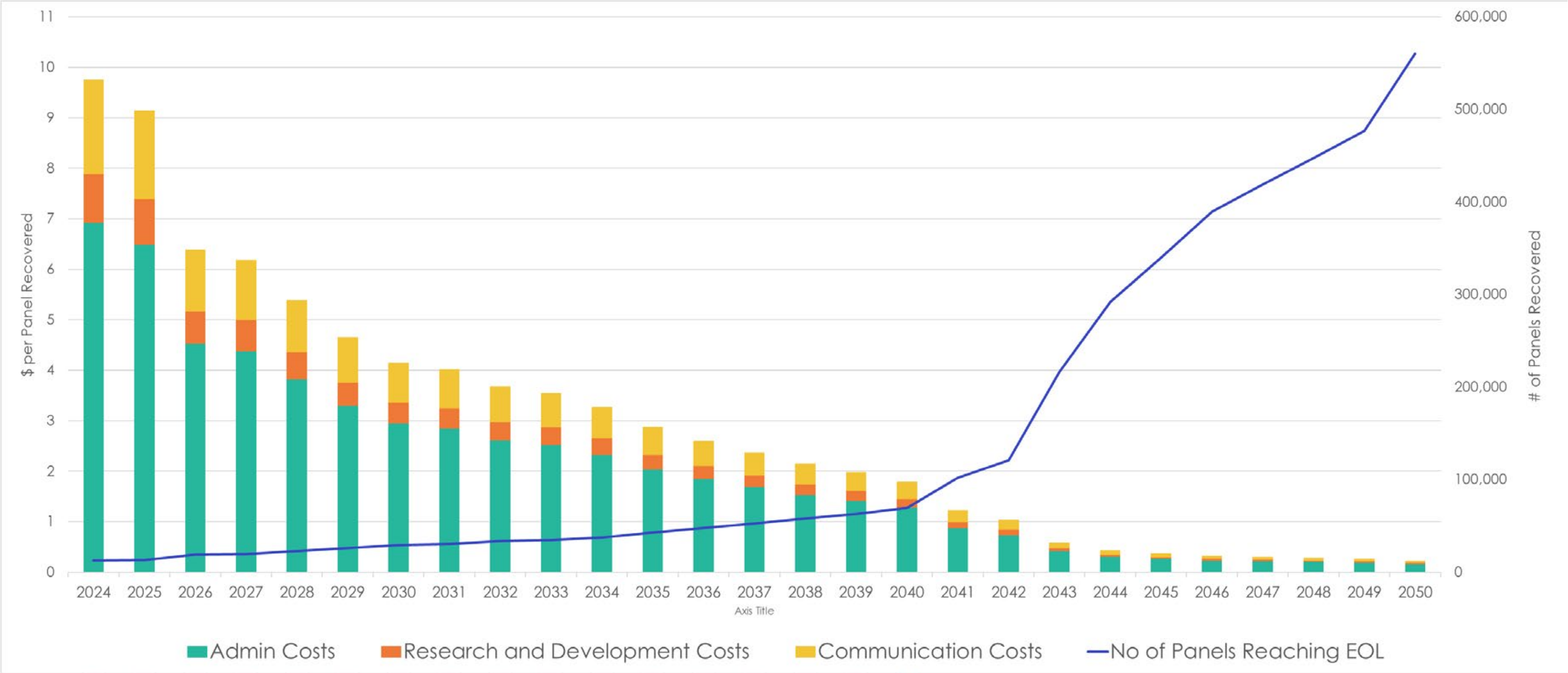


Figure 49 shows the program management costs per panel from 2024 to 2050 for Scenarios 3a, Scenario 3b, Scenario 4 (Full EPR) and Scenario 5 (Decommissioning for Utility, Full EPR for all other). These costs are highest in 2024 at just under $10 per panel as the smallest number of solar PV panels reach EOL in 2024. In 2050, when the greatest number of solar PV panels reach EOL these costs total ~$0.25 per panel. This may be a cost to "ramp up" as volume comes in.

Figure 49. Program Management Costs per Panel – Scenarios 3a, Scenario 3b, Scenario 4 and Scenario 5



Revenue from Material Sales Assumptions

To calculate the potential revenue available from the sale of material components from EOL solar PV panels Eunomia used revenue per panel figures taken from an analysis on the recycling process of solar PV panels.[44] These figures are shown in Table 29.

Table 29. Revenue from the Sale of Material Components by Recycling Yield

	Revenue ($/panel)	Net Cost of Recycling ($/Panel)	Gross Cost of Recycling ($/Panel)
Limited Recovery	3.00	10	13
Comprehensive Recovery	8.20	20	28.2

Figure 50 shows the total revenue available from the sale of EOL solar PV panels material components for each of the six scenarios in 2030, 2040 and 2050. Total revenues are highest in 2050 as this is when the greatest amount of solar PV panels reach EOL. Scenario 4 (Full EPR) has the highest potential revenue at ~$3.7 million in 2050, followed by Scenario 2 (Landfill Ban with Targets) and Scenario 5 (Decommissioning for Utility, EPR for all other) with potential revenues of ~$2.9 million. The cost which is charged to those dropping off panels is the net cost of recycling.

Figure 50. Total Revenue available from the Sale of EOL Solar PV Panel Material Components

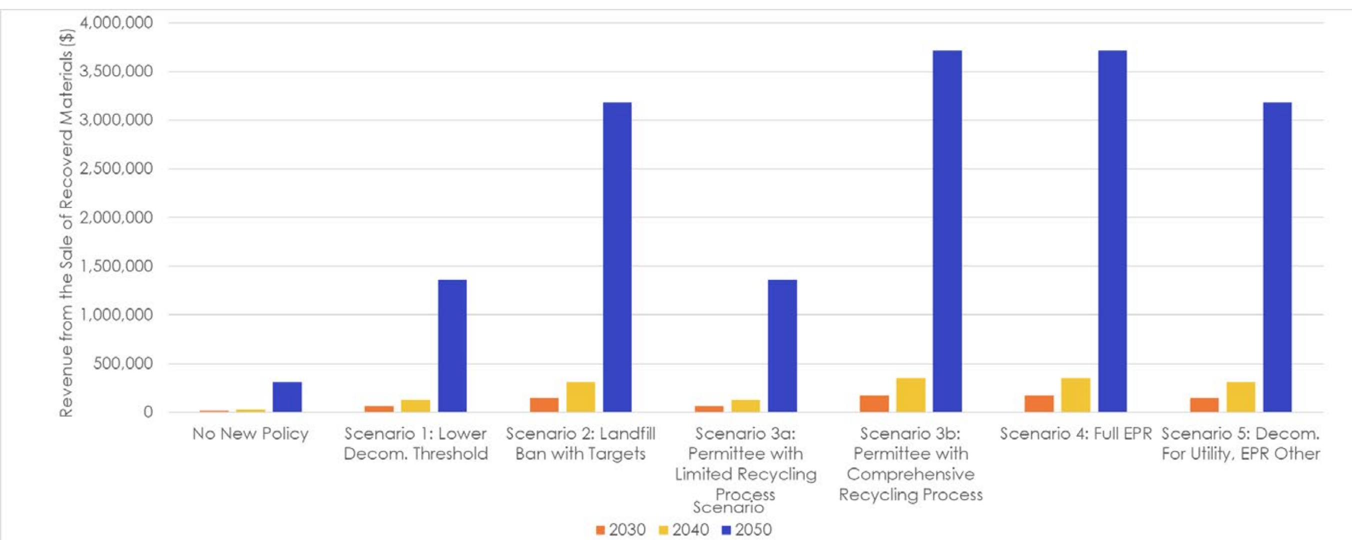


Figure 50 reflects that Scenarios 2, 3b, 4 and 5 have the highest overall revenue generated as a result of comprehensive recycling for most panels. Scenarios 2 and 5 are slightly lower that Scenario 4 as the utility sector is assumed to have limited recycling.

3.4 Cost Summary in 2050

This section shows the total and per panel costs for each sector, by scenario and activity. The section is laid out by scenario. For panels which are not recycled under No New Policy and Scenario 1, there are disposal costs associated with those panels. These costs, plus the recycling only costs, add up to the Total Management Costs of EOL solar panels.

3.4.1 No New Policy

Table 30 shows the total costs (in $USD) by activity and sector in the No New Policy scenario. This scenario has a total cost of $2.2 million dollars for the management of all panels, and $1.6 million for panels which are recycled. Only Utility panels are recycled in this scenario, while some Utility and all other panels are assumed to be disposed.

Table 30. Total Costs by Activity and Sector in the No New Policy Scenario

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	0	94,000	86,000	0	0	**180,000**
Depot Reception	0	0	0	0	0	**0**
Recycling Transportation	630,000	0	0	0	0	**630,000**
Recycling: Limited	750,000	0	0	0	0	**750,000**
Recycling: Comprehensive	0	0	0	0	0	**0**
Disposal	140,000	62,000	57,000	40	340,000	**600,000**
Program Management	0	0	0	0	0	**0**
Total - All Management	**1,500,000**	**160,000**	**140,000**	**40**	**340,000**	**2,200,000**
Total - Recycling Only	**1,400,000**	**0**	**0**	**0**	**0**	**1,400,000**

Table 31 shows the costs per panel (in $USD) by activity and sector in the No New Policy scenario.

Table 31. Costs Per Panel by Activity and Sector in the No New Policy Scenario

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	--	2.0	2.0	--	--	**2.0**
Depot Reception	--	0.0	0.0	--	--	**0.0**
Recycling Transportation	6.4	--	--	--	--	**6.4**
Recycling: Limited	7.5	--	--	--	--	**7.5**
Recycling: Comprehensive	--	--	--	--	--	**--**
Disposal	1.3	1.3	1.3	1.3	1.3	**1.3**
Program Management	--	--	--	--	--	**0.0**
Total - All Management	**7.4**	**3.3**	**3.3**	**1.3**	**1.3**	**3.8**
Total - Recycling Only	**13.9**	**--**	**--**	**--**	**--**	**13.9**

3.4.2 Scenario 1: Lower Decommissioning Threshold

Table 32 shows the total costs (in $USD) by activity and sector in Scenario 1: Lower Decommissioning Threshold. Scenario 1 sees more recycling for the Utility sector, with a total of $6.4 million being spent on recycling activities. The recycling cost for those panels is $13.6 per panel. This is slightly lower than No New Policy due to efficiencies with economies of scale as more panels are recycled.

Table 32. Total Costs by Activity and Sector in Scenario 1 (Lower Decommissioning Threshold)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	0	94,000	86,000	0	0	**180,000**
Depot Reception	0	150,000	140,000	30	0	**300,000**
Recycling Transportation	1,300,000	0	0	170	1,700,000	**3,000,000**
Recycling: Limited	1,500,000	0	0	190	1,900,000	**3,400,000**
Recycling: Comprehensive	0	0	0	0	0	**0**
Disposal	0	62,000	57,000	0	0	**120,000**
Program Management	0	0	0	0	0	**0**
Total - All Management	**2,800,000**	**310,000**	**280,000**	**400**	**3,600,000**	**7,000,000**
Total - Recycling Only	**2,800,000**	**0**	**0**	**400**	**3,600,000**	**6,400,000**

Table 33 shows the costs per panel (in $USD) by activity and sector in Scenario 1: Lower Decommissioning Threshold.

Table 33. Costs Per Panel by Activity and Sector in Scenario 1 (Lower Decommissioning Threshold)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	--	2.0	2.0	--	--	**2.0**
Depot Reception	--	3.2	3.2	--	--	**3.2**
Recycling Transportation	6.4	--	--	6.4	6.4	**6.4**
Recycling: Limited	7.5	--	--	7.0	7.0	**7.2**
Recycling: Comprehensive	--	--	--	--	--	**--**
Disposal	--	1.3	1.3	--	--	**1.3**
Program Management	--	--	--	--	--	**0.0**
Total - All Management	**13.9**	**6.5**	**6.5**	**14.5**	**13.4**	**12.5**
Total - Recycling Only	**13.9**	**--**	**--**	**14.5**	**13.4**	**13.6**

3.4.3 Scenario 2: Landfill Ban with Recycling Targets

Table 34 shows the total costs (in $USD) by activity and sector in Scenario 2: Landfill Ban with Recycling Targets. Scenario 2 is the first scenario that includes recycling costs for non-utility panels. The total cost for recycling is therefore $10.6 million, about $4 million higher than Scenario 1. Because this scenario is a continuation of the decommissioning plans for Utility panels, those panels are sent for limited recycling, while the rest of the panels are sent for comprehensive recycling. As a result, the cost per panel for non-utility panels is nearly double that of Utility panels.

Table 34. Total Costs by Activity and Sector in Scenario 2 (Landfill Ban with Recycling Targets)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	0	94,000	86,000	0	0	**180,000**
Depot Reception	0	150,000	140,000	30	0	**300,000**
Recycling Transportation	1,300,000	300,000	280,000	170	1,700,000	**3,600,000**
Recycling: Limited	1,500,000	0	0	0	0	**1,500,000**
Recycling: Comprehensive	0	670,000	620,000	380	3,700,000	**5,000,000**
Disposal	0	0	0	0	0	**0**
Program Management	0	0	0	0	0	**0**
Total - All Management	**2,800,000**	**1,200,000**	**1,100,000**	**590**	**5,400,000**	**10,600,000**
Total - Recycling Only	**2,800,000**	**1,200,000**	**1,100,000**	**590**	**5,400,000**	**10,600,000**

Table 35 shows the costs per panel (in $USD) by activity and sector in Scenario 2: Landfill Ban with Recycling Targets.

Table 35. Costs per Panel by Activity and Sector in Scenario 2 (Landfill Ban with Recycling Targets)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	--	2.0	2.0	--	--	**2.0**
Depot Reception	--	3.2	3.2	--	--	**3.2**
Recycling Transportation	6.4	6.4	6.4	6.4	6.4	**6.4**
Recycling: Limited	7.5	--	--	--	--	**7.5**
Recycling: Comprehensive	--	14.1	14.1	14.1	14.1	**14.1**
Disposal	--	--	--	--	--	**--**
Program Management	--	--	--	--	--	**0.0**
Total - All Management	**13.9**	**25.7**	**25.7**	**21.5**	**20.5**	**18.9**
Total - Recycling Only	**13.9**	**25.7**	**25.7**	**21.5**	**20.5**	**18.9**

3.4.4 Scenario 3a: Permittee with Limited Recycling

Table 36 shows the total costs (in $USD) by activity and sector in Scenario 3a: Permittee with Limited Recycling. Under scenario 3a, there is limited recycling for all sectors. The resulting total cost comes out to $8 million, which is lower than Scenario 2. The cost per panel to recycle panels is similar across sectors, from $13.4 to $16.5 per panel with CSG on the lower end. Under limited recycling, utility has slightly higher costs because it includes a small number of thin-film panels which are assumed to be 25% more expensive to recycle than silica panels. Depot reception costs in this scenario are lower as they assume private, dedicated collection sites.

Table 36. Total Costs by Activity and Sector in Scenario 3a (Permittee with Limited Recycling)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	0	94,000	86,000	0	0	**180,000**
Depot Reception	0	51,000	47,000	30	0	**99,000**
Recycling Transportation	1,300,000	300,000	280,000	170	1,700,000	**3,600,000**
Recycling: Limited	1,500,000	330,000	310,000	190	1,900,000	**4,000,000**
Recycling: Comprehensive	0	0	0	0	0	**0**
Disposal	0	0	0	0	0	**0**
Program Management	0	0	0	0	0	**130,000**
Total - All Management	**2,800,000**	**780,000**	**720,000**	**400**	**3,600,000**	**8,000,000**
Total - Recycling Only	**2,800,000**	**780,000**	**720,000**	**400**	**3,600,000**	**8,000,000**

Table 37 shows the costs per panel (in $USD) by activity and sector in Scenario 3a: Permittee with Limited Recycling.

Table 37. Costs Per Panel by Activity and Sector in Scenario 3a (Permittee with Limited Recycling)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	--	2.0	2.0	--	--	**2.0**
Depot Reception	--	1.1	1.1	--	--	**1.1**
Recycling Transportation	6.4	6.4	6.4	6.4	6.4	**6.4**
Recycling: Limited	7.5	7.0	7.0	7.0	7.0	**7.2**
Recycling: Comprehensive	--	--	--	--	--	**--**
Disposal	--	--	--	--	--	**--**
Program Management	--	--	--	--	--	**0.2**
Total - All Management	**13.9**	**16.5**	**16.5**	**14.5**	**13.4**	**14.3**
Total - Recycling Only	**13.9**	**16.5**	**16.5**	**14.5**	**13.4**	**14.3**

3.4.5 Scenario 3b: Permittee with Comprehensive Recycling

Table 38 shows the total costs (in $USD) by activity and sector in Scenario 3b: Permittee with Comprehensive Recycling. This scenario is $2.5 million more expensive than the permittee with limited recycling scenario (Scenario 3a). The difference is entirely due to the introduction of comprehensive recycling for utility, residential, commercial, industrial, and CSG sectors

Table 38. Total Costs by Activity and Sector in Scenario 3b (Permittee with Comprehensive Recycling)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	0	94,000	86,000	0	0	**180,000**
Depot Reception	0	51,000	47,000	30	0	**99,000**
Recycling Transportation	1,300,000	300,000	280,000	170	1,700,000	**3,600,000**
Recycling: Limited	0	0	0	0	0	**0**
Recycling: Comprehensive	3,100,000	670,000	620,000	380	3,700,000	**8,100,000**
Disposal	0	0	0	0	0	**0**
Program Management	0	0	0	0	0	**130,000**
Total - All Management	**4,400,000**	**1,100,000**	**1,000,000**	**590**	**5,400,000**	**12,100,000**
Total - Recycling Only	**4,400,000**	**1,100,000**	**1,000,000**	**590**	**5,400,000**	**12,100,000**

Table 39 shows the costs per panel (in $USD) by activity and sector in Scenario 3b: Permittee with Comprehensive Recycling.

Table 39. Costs Per Panel by Activity and Sector in Scenario 3b (Permittee with Comprehensive Recycling)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	--	2.0	2.0	--	--	**2.0**
Depot Reception	--	1.1	1.1	--	--	**1.1**
Recycling Transportation	6.4	6.4	6.4	6.4	6.4	**6.4**
Recycling: Limited		--	--	--	--	**7.5**
Recycling: Comprehensive	15.0	14.1	14.1	14.1	14.1	**14.1**
Disposal	--	--	--	--	--	**--**
Program Management	--	--	--	--	--	**0.2**
Total - All Management	**13.9**	**23.5**	**23.5**	**21.5**	**20.5**	**18.8**
Total - Recycling Only	**13.9**	**23.5**	**23.5**	**21.5**	**20.5**	**18.8**

3.4.6 Scenario 4: EPR for All Sectors

Table 40 shows the total costs (in $USD) by activity and sector in Scenario 4: EPR for All Sectors. This scenario is the costliest scenario at $12.1 million. In this scenario, every sector has comprehensive recycling and all panels are recovered for recycling.

Table 40. Total Costs by Activity and Sector in Scenario 4 (EPR for All Sectors)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	0	94,000	86,000	0	0	**180,000**
Depot Reception	0	51,000	47,000	30	0	**99,000**
Recycling Transportation	1,300,000	300,000	280,000	170	1,700,000	**3,600,000**
Recycling: Limited	0	0	0	0	0	**0**
Recycling: Comprehensive	3,100,000	670,000	620,000	380	3,700,000	**8,100,000**
Disposal	0	0	0	0	0	**0**
Program Management	0	0	0	0	0	**130,000**
Total - All Management	**4,400,000**	**1,100,000**	**1,000,000**	**590**	**5,400,000**	**12,100,000**
Total - Recycling Only	**4,400,000**	**1,100,000**	**1,000,000**	**590**	**5,400,000**	**12,100,000**

Table 41 shows the costs per panel (in $USD) by activity and sector in Scenario 4: EPR for All Sectors.

Table 41. Costs Per Panel by Activity and Sector in Scenario 4 (EPR for All Sectors)

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	--	2.0	2.0	--	--	**2.0**
Depot Reception	--	1.1	1.1	--	--	**1.1**
Recycling Transportation	6.4	6.4	6.4	6.4	6.4	**6.4**
Recycling: Limited	--	--	--	--	--	**--**
Recycling: Comprehensive	15.0	14.1	14.1	14.1	14.1	**14.4**
Disposal	--	--	--	--	--	**--**
Program Management	--	--	--	--	--	**0.2**
Total - All Management	**21.4**	**23.5**	**23.5**	**21.5**	**20.5**	**21.5**
Total - Recycling Only	**21.4**	**23.5**	**23.5**	**21.5**	**20.5**	**21.5**

3.4.7 Scenario 5: Decommissioning for Utility – EPR for All Other Sectors

Table 42 shows the total costs (in $USD) by activity and sector in Scenario 5: Decommissioning for Utility – EPR for All Other Sectors. Scenario 5 incurs a similar cost to scenario 2, as it involves comprehensive recycling for all sectors except for utility, which continues to have its decommissioning based management with limited recycling. In this scenario there will be higher recovery of non-utility panels through the EPR program, compared to Scenario 2, with associated cost efficiencies.

Table 42. Total Costs by Activity and Sector in Scenario 5 (Decommissioning for Utility – EPR for All Other Sectors)

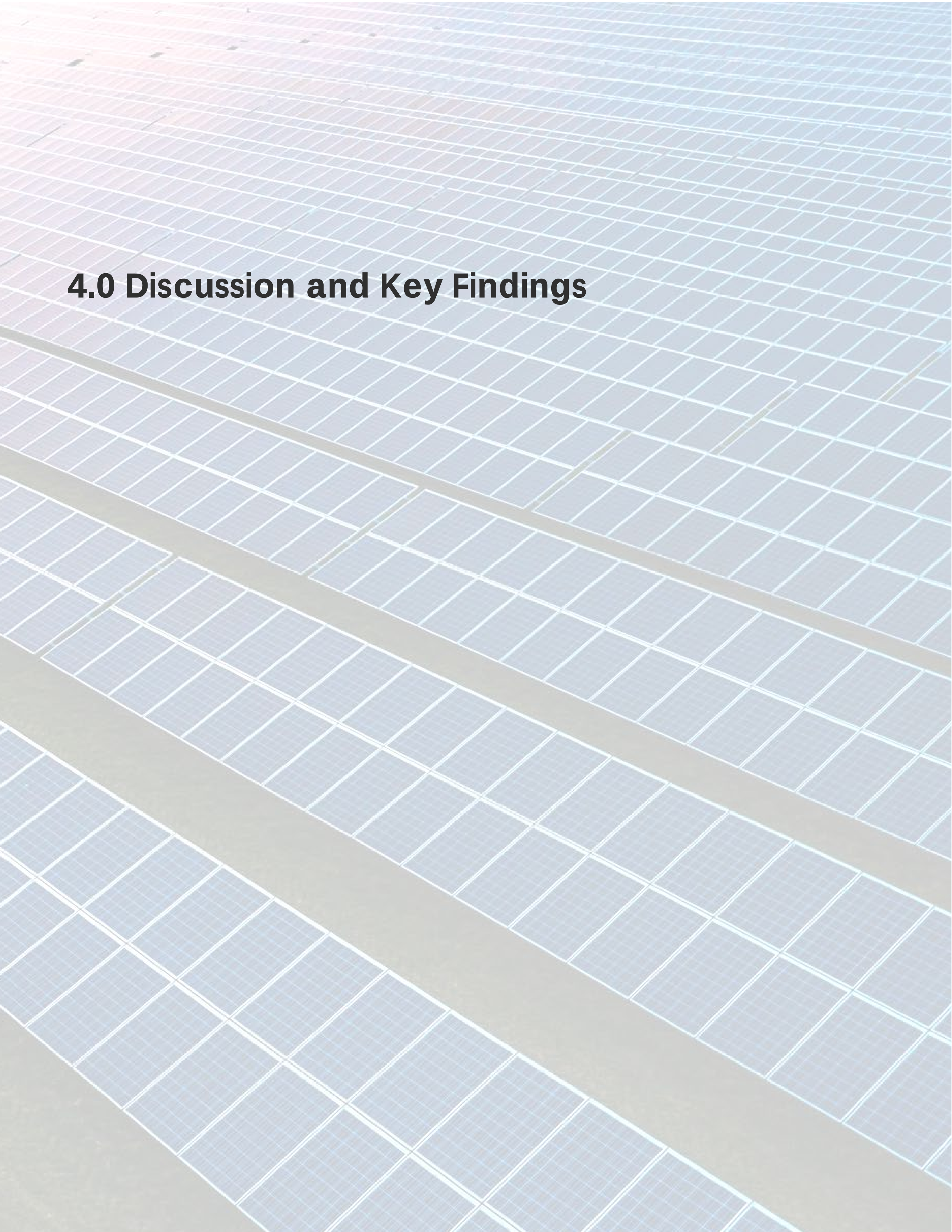
Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	0	94,000	86,000	0	0	**180,000**
Depot Reception	0	51,000	47,000	30	0	**99,000**
Recycling Transportation	1,300,000	300,000	280,000	170	1,700,000	**3,600,000**
Recycling: Limited	1,500,000	0	0	0	0	**1,500,000**
Recycling: Comprehensive	0	670,000	620,000	380	3,700,000	**5,000,000**
Disposal	0	0	0	0	0	**0**
Program Management	0	0	0	0	0	**130,000**
Total - All Management	**2,800,000**	**1,100,000**	**1,000,000**	**590**	**5,400,000**	**10,500,000**
Total - Recycling Only	**2,800,000**	**1,100,000**	**1,000,000**	**590**	**5,400,000**	**10,500,000**

Table 43 shows the costs per panel (in $USD) by activity and sector in Scenario 5: Decommissioning for Utility – EPR for All Other Sectors.

Table 43. Costs Per Panel by Activity and Sector in Scenario 5 (Decommissioning for Utility – EPR for All Other Sectors

Cost Item	Utility	Residential	Commercial	Industrial	CSG	Total
Initial Collection	--	2.0	2.0	--	--	**2.0**
Depot Reception	--	1.1	1.1	--	--	**1.1**
Recycling Transportation	6.4	6.4	6.4	6.4	6.4	**6.4**
Recycling: Limited	7.5	--	--	--	--	**7.5**
Recycling: Comprehensive	--	14.1	14.1	14.1	14.1	**14.1**
Disposal	--	--	--	--	--	**--**
Program Management	--	--	--	--	--	**0.2**
Total - All Management	**13.9**	**23.5**	**23.5**	**21.5**	**20.5**	**18.8**
Total - Recycling Only	**13.9**	**23.5**	**23.5**	**21.5**	**20.5**	**18.8**

4.0 Discussion and Key Findings



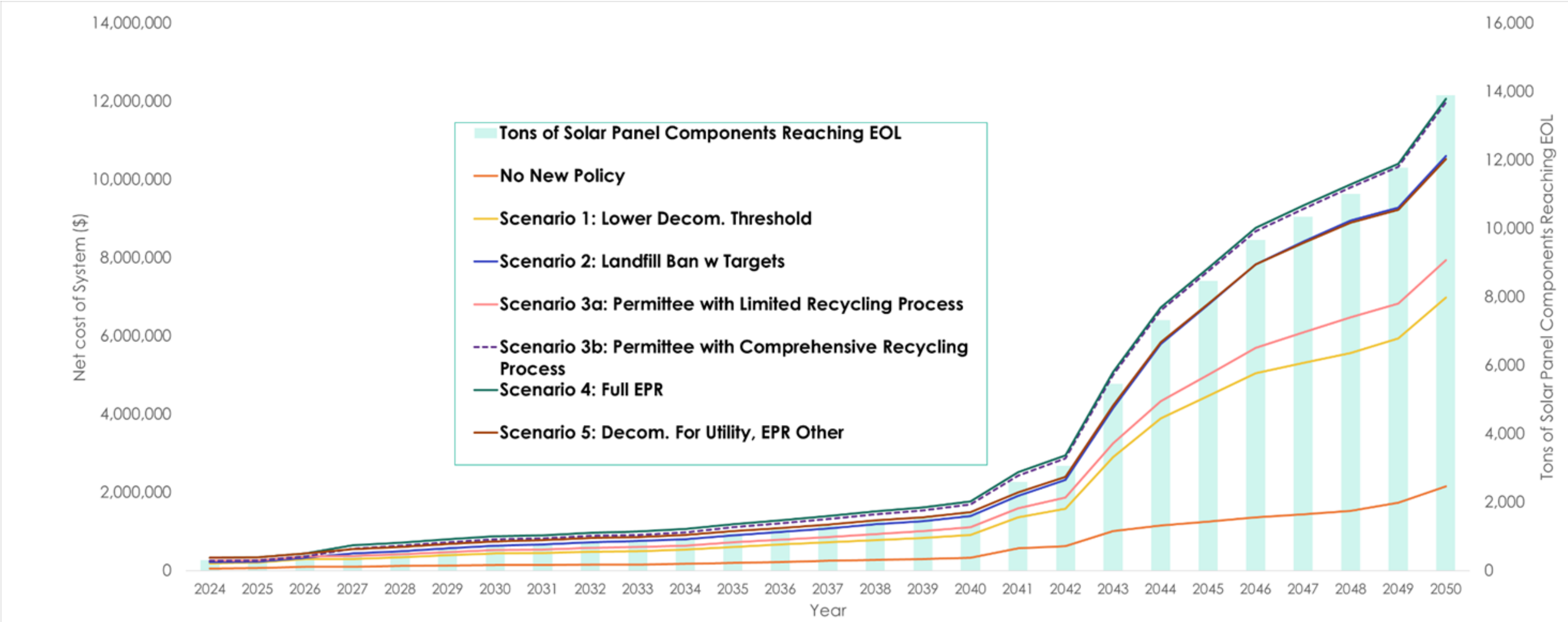
4.1 Summary of Statewide Results across Scenarios

4.1.1 Annual Net Costs

Total System Net Costs include initial collection costs, consolidation costs, recycler transportation costs, dismantling/recycling costs, and program management costs. Program management costs include operations and administrative costs, research and development costs, and communication costs. Deinstallation costs are not included in Total System Net Costs as Eunomia assumed that EOL solar PV panels would have to be uninstalled regardless of whether they were going to be recycled or going to landfill. Additionally, the purpose of policy is to ensure the material is taken to recycling, all scenarios except for the No New Policy Scenario require 100% collection (as mandated by Minnesota Session Laws Chapter 60, Article 3, Section 36), meaning that even scenarios without policies devoted to specific sectors have costs to manage solar PV panels.

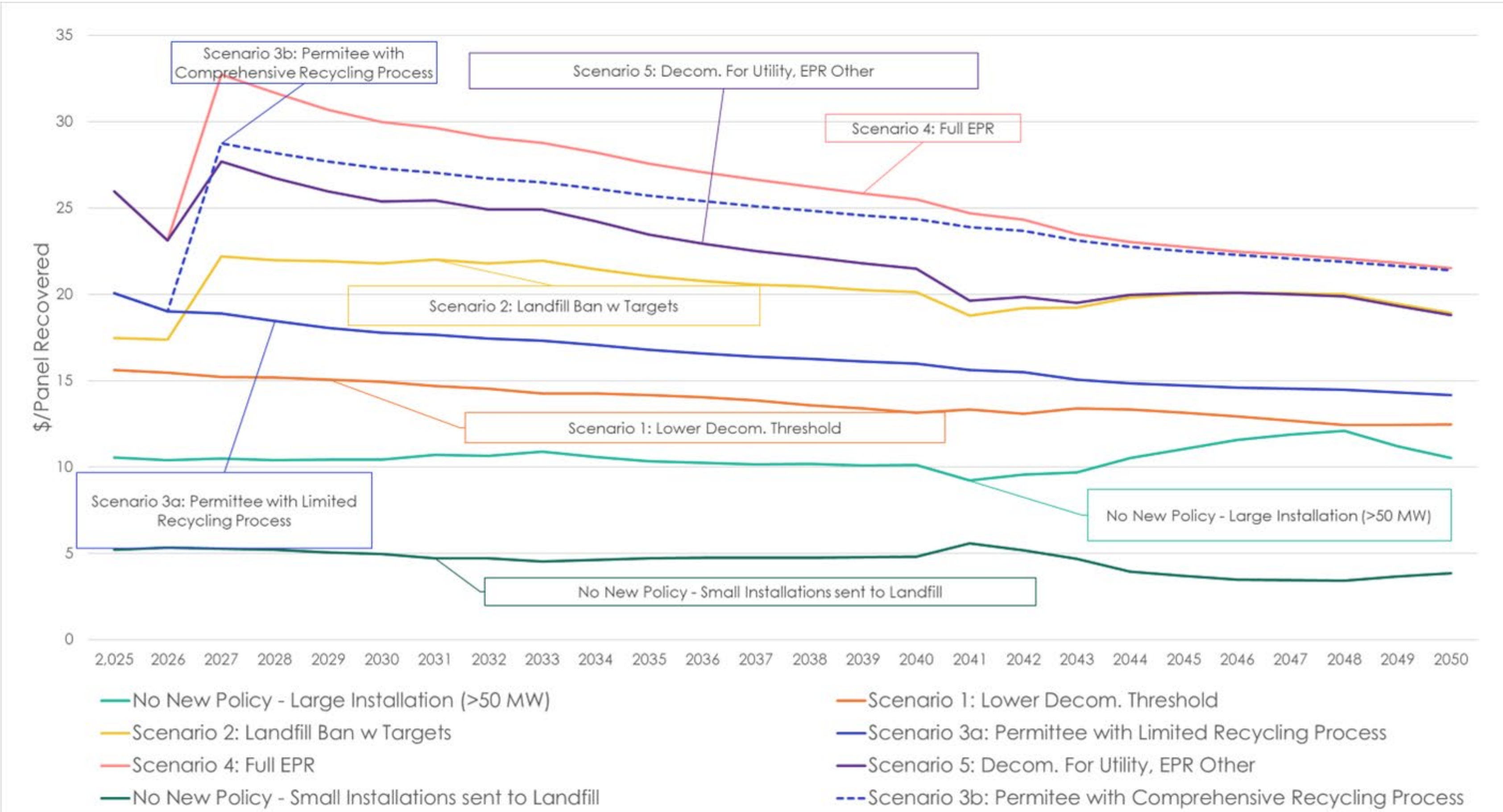
The costs are shown for each scenario in Figure 51, against the total tons of solar PV panels reaching EOL from 2024 to 2050. The lines in the chart represent the annual net cost of each scenario, while the bar graph shows the total tons of solar PV panels reaching EOL each year. Costs are highest in 2050, as the largest number of solar PV panels are coming offline this year. Scenario 4 (Full EPR) and Scenario 3b present the highest total system costs of ~$12.1 million in 2050, followed by Scenario 2 (Landfill Ban with Targets) which has costs of ~$10.6 million in 2050 and the Permittee with Comprehensive Recycling Process which has costs of ~$10.5 million. Scenario 1 (Lower Decommissioning Threshold) and Scenario 5 (Decommissioning for Utility, EPR for all others) have costs of ~$6.9 million and ~$10.5 million.

Figure 51. Total System Net Costs and Annual Tons of Solar PV Panels Reaching EOL from 2024 to 2050



In each scenario, the cost of the program spikes around 2040, and then has a cost curve which becomes less steep. This reflects the cost per panel or per ton decreasing over time as recycling costs decrease. This decrease can be seen when the costs are placed on a per panel basis. Figure 52 shows the annual costs per panel recovered for each scenario, from 2025 to 2050.

Figure 52. Cost per Panel Recovered by Scenario



In each of the scenarios with policy, the cost per panel line is smoother and has a slight decrease over time as the cost to recycle panels decreases. The no new policy scenario has a much more varied cost, as the cost per panel is reliant on panels from solar installations greater than 50 MW coming offline.

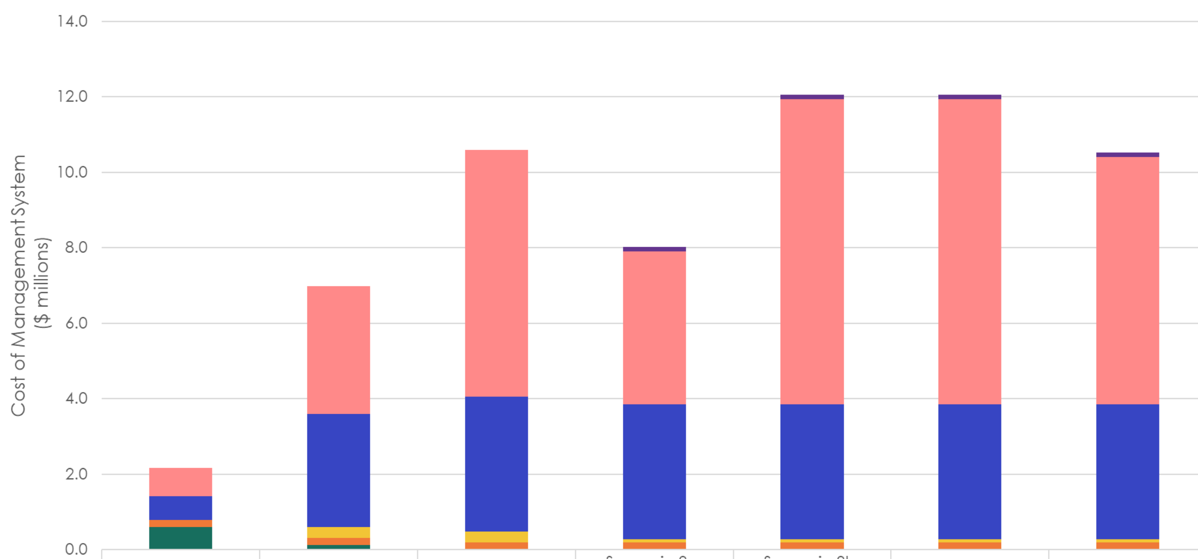
4.1.2 Costs by Activity

This section analyses the total costs of recycling solar PV panels by activity type. As mentioned in Section 3.3, there are five main modules of costs included in the estimate of EOL solar PV panel management:

- Initial Collection of solar PV panels
- Transportation to a recycler
- Depot reception of solar PV panels
- Solar PV panel recycling/dismantling
- Program management costs

Figure 53 below shows the total costs of the recycling system for 2050 for each modelled scenario. The costs are broken down by each of the activities mentioned in the list above. Note that there is an estimated $600,000 for disposal of solar panels from all sectors in the 'No New Policy' baseline. See Section 3.4.1, Table 30 for details.

Figure 53. Total Cost by Activity in 2050



	No New Policy	Scenario 1: Lower Decom. Threshold	Scenario 2: Landfill Ban w Targets	Scenario 3a: Permittee with Limited Recycling Process	Scenario 3b: Permittee with Comprehensive Recycling Process	Scenario 4: Full EPR	Scenario 5: Decom. For Utility, EPR Other
Program Management	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Recycling	0.7	3.4	6.6	4.0	8.1	8.1	6.6
Recycler Transportation	0.6	3.0	3.6	3.6	3.6	3.6	3.6
Depot Reception	0.0	0.3	0.3	0.1	0.1	0.1	0.1
Initial Collection	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Disposal	0.6	0.1	0.0	0.0	0.0	0.0	0.0

In all scenarios, the greatest cost to the system in 2050 is the actual recycling process of the solar PV panels. This varies from ~$750,000 in the no new policy scenario to ~$8 million in the Full EPR scenario. The other costs remain relatively stable, as the logistics of the system are similar across scenarios. The exception is in depot reception costs. Scenarios with more comprehensive recycling such as the Landfill Ban with Targets, Full EPR, and Decommissioning for Utility, EPR Other have higher total costs between~$10 and ~$12 million each. Recycling transportation is similar in each scenario as all panels must be sent for recovery.

These costs are placed on a cost per panel and cost per ton basis in Table 44. De-installation costs are shown in this table as well despite not being assumed to fall under the payment for policies. This is to illustrate the comparative cost of the other recycling activities with the cost to de-install a panel.

Table 44. Cost per Panel and Cost per Ton by Activity in 2050

	Cost per Panel							Cost per Ton						
	No New Policy	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**	**No New Policy**	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**
De-Installation	103	103	103	103	103	103	103	4,147	4,147	4,147	4,147	4,147	4,147	4,147
Recycling Activities Attributable to Policy:														
Initial Collection	0.0	0.4	0.3	0.3	0.3	0.3	0.3	0.0	15	14	15	14	14	14
Depot Reception	0.0	0.6	0.5	0.2	0.2	0.2	0.2	0	25	23	8	8	8	8
Recycler Transportation	6.4	6.4	6.4	6.4	6.4	6.4	6.4	135	250	283	299	274	274	283
Recycling	7.5	7.5	11.7	7.2	14.4	14.4	11.7	149	284	519	338	620	620	519
Program Management	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0	0	0	11	10	10	10
Total Recycling Activities	**13.9**	**15**	**19**	**14**	**22**	**22**	**19**	**285**	**574**	**840**	**670**	**926**	**926**	**835**

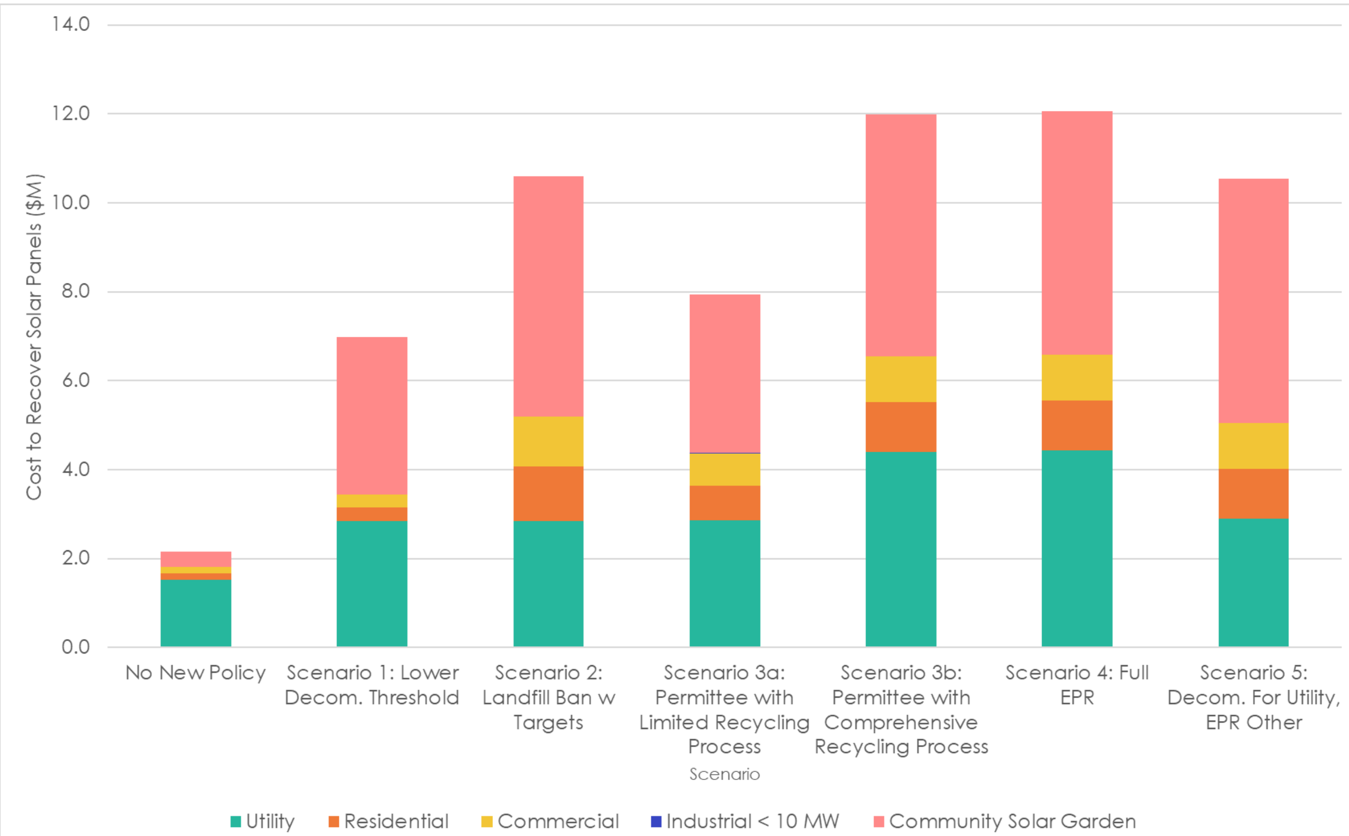
The full program cost per panel for recovery and recycling in 2050 ranges from $14-$22 per panel for scenarios with new policy. The full program cost per ton for recovery and recycling ranges from $574 to $926 per ton. Recycling alone varies from $7-$14 per panel, and $149-$620 per ton. Program management represents only $0.2 per panel recovered in the highest cost scenario, and $9 per ton. Note that under 'No New Policy' the cost per panel only applies to the Utility sector panels that are being recovered and recycled. In Scenario 1 the cost per panel applies to the panels being recovered from installations over 1MW in size and a small number of panels from smaller installations.

4.1.3 Costs by Sector

This section investigates the cost of the system by generating sector. The total annual cost in 2050 for each sector is shown in Figure 54. The five sectors were categorized as the generators for EOL solar PV panels as listed below:

- Utility
- Commercial
- Residential
- Industrial
- Community Solar Garden

Figure 54. Total Annual Costs by Sector in 2050



In each scenario that includes policy, CSGs represent the greatest total cost to the system. This is driven primarily by two factors:

- CSGs have historically had the most installations of any sector, and thus have the most volume
- CSG installations are generally above 1 MW and are likely to be taken to a more national recycler out of state for comprehensive recycling.

Utility sector total costs are about $2.8 million in Scenarios 1, 2, 3a, and 5 with limited recycling, and about $4.4 million in Scenarios 3b and 4 with comprehensive recycling. Residential and commercial sectors together have total costs of about $2 million in scenarios 2, 3b, 4, and 5 with comprehensive recycling, and about 1.5 million in Scenario 3a with limited recycling. See section 3.4 for additional detail. Table 45 below shows the cost per panel and cost per ton for each sector under each scenario.

Table 45. Cost per Panel and Cost per Ton of Recovering Solar PV Panels in 2050, by Sector

		Cost per Panel ($/Panel)							Cost per ton ($/Ton)					
	No New Policy	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**	**No New Policy**	**Scenario 1: Lower Decom. Threshold**	**Scenario 2: Landfill Ban w Targets**	**Scenario 3a: Permittee w/Limited Recycling**	**Scenario 3b: Permittee w/Compre-hensive Recycling**	**Scenario 4: Full EPR**	**Scenario 5: Decom. For Utility, EPR Other**
Utility	13.9	14	14	14	21	22	14	285	606	606	610	861	867	616
Residential	*	*	26	17	24	24	24	*	*	1,402	984	1,288	1,296	1,296
Commercial	*	*	26	17	24	24	24	*	*	1,121	787	1,031	1,037	1,037
Industrial < 10 MW	*	15	22	15	22	22	22	*	862	1,176	867	1,180	1,188	1,188
Community Solar Garden	*	13	20	14	21	21	21	*	638	894	642	897	904	904

** No panels/tons recycled.*

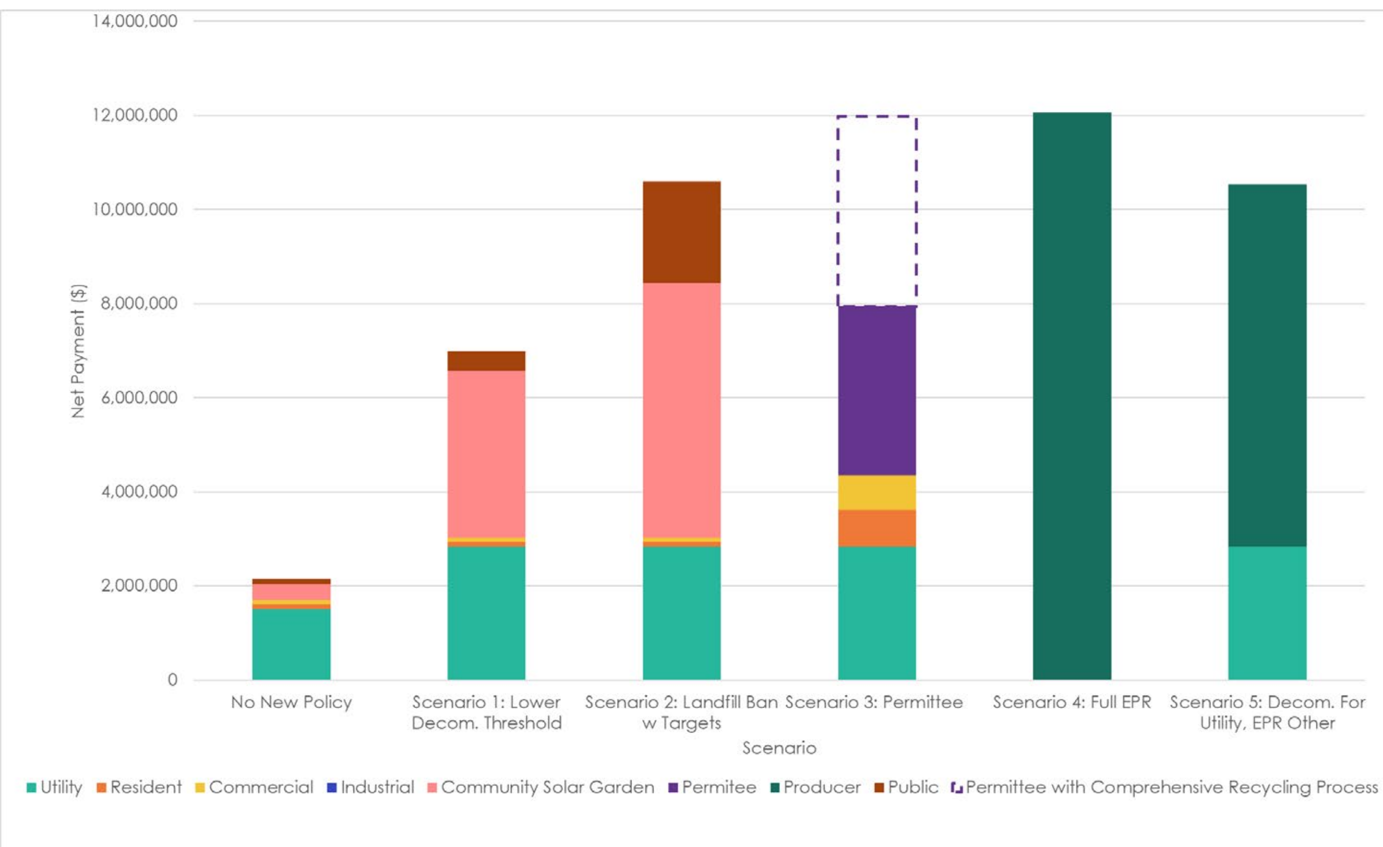
Solar PV panels that are in higher volume arrays, such as utility and CSG, have a lower cost per panel and cost per ton than residential and commercial installations. Utility and CSG installations range from $13-$22 per panel under scenarios which introduce policy, or $606-$904 per ton. Residential and commercial installations range from $17-26 per panel, or $1,031-$1,296 per ton. Scenario 3-b and Scenario 4 are the only scenarios with comprehensive recycling for the utility sector, and the only scenarios where all sectors have the same recycling levels. Under these scenarios, the residential and commercial sector costs per panel are 10-15% more expensive than for the CSG and Utility sector costs per panel. The initial collection and consolidation needs for residential and commercial panels increase the cost to manage those modules above the cost for CSG and utility panels. These costs can be reduced if a comprehensive EOL program is established and/or there is a focus on lower cost consolidation sites.

The utility sector has a cost per panel of $13-14/panel for three out of five scenarios with new policy. In these three scenarios, the utility sector has limited recovery as its recycling process as this is the assumed recycling processing for "decommissioning only" policies without recycling targets.

The exceptions are full EPR and permittee with comprehensive recycling where utility sector panels are subject to comprehensive recycling.

The residential and commercial sectors have a cost per panel of $24 when under EPR and $26 in the landfill ban with targets scenario. The cost under the Landfill Ban with Targets scenario is higher as this scenario assumes higher costs of sorting at depots which are not dedicated to solar PV panels but may handle other material waste streams as well. Both the EPR and landfill ban with targets scenario have comprehensive recycling assumptions, but it is assumed that there will be dedicated solar consolidation facilities under EPR. The Permittee With Limited Recycling Process scenario is the cheapest scenario for residential and commercial because the recycling process is limited and focused on glass and aluminum recovery only rather than comprehensive recycling for all metals and semiconductor materials. Additionally, this scenario has dedicated consolidation facilities which are lower cost per panel to operate than facilities which take other materials. The funding source for the program also varies by scenario, Figure 55 shows how the payments change based on the structure of the policy in place.

Figure 55. Cost Burden by Scenario 2050



Under the permittee pays scenario, the solid bars represent the costs where there are limited recycling processes, while the dashed box represents the additional cost when assuming a comprehensive recycling scenario for all sectors.

In the chart, the scenarios without dedicated funding sources, such as the Lower Decommissioning Threshold (>1MW) and Landfill Ban with Targets scenario, see costs being placed on the owners of the solar arrays. This means that the owners or permittees of residential, commercial, and community solar garden installations will pay the costs of recycling. However, in these two scenarios there is not an explicit 'owner pays' policy or requirement as there is for both variations in Scenario 3.

Under the scenarios with dedicated funding sources for the end of life (the EPR scenarios), costs are borne by the producers and importers of the solar PV panels. Residents and businesses do not have to pay for management of solar PV panels under these scenarios, except in Scenario 5, utilities are covering the costs of managing their panels. In some EPR programs, a purchaser may pay a stewardship assessment at the time of purchase and does contribute to end of life management costs.

Under the permittee pays structure for Scenario 3, some or all of the costs are paid for by the owners/permittees of the solar arrays as they will pay for the post-collection portion of the costs.

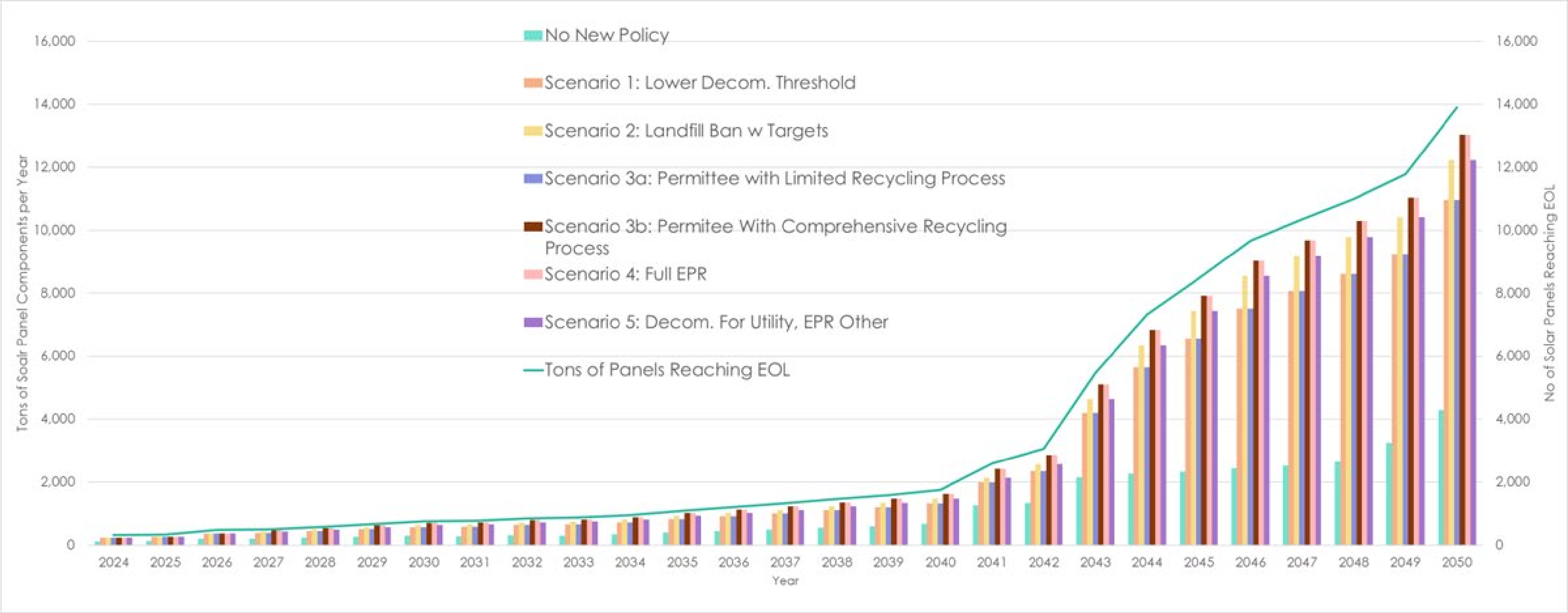
While the annual net costs all increase as solar PV panels come offline, what drives variation the most in costs between scenarios is the differences in recycling rate of those EOL panels, as discussed in the following section.

4.2 Recycling Rates

Recycling rates refer to the percent of material components recycled from EOL solar PV panels. Eunomia calculated these rates by weight, dividing the total tons of EOL solar PV panel components recycled by the total tons of EOL solar PV panels in each given year, for each scenario. Each scenario has a lead in time of a few years where recycling yields are lower than steady state when using the comprehensive recycling processes.

The bars in Figure 56 show the projected tons of EOL solar PV panel components that will be recycled in each scenario. The line shows the projected tons of solar PV panels reaching EOL. These are the highest in 2050, as this is when the greatest number of solar PV panels reach EOL. Scenario 4, Full EPR, which has a comprehensive recycling level, has the greatest number of recycled tons.

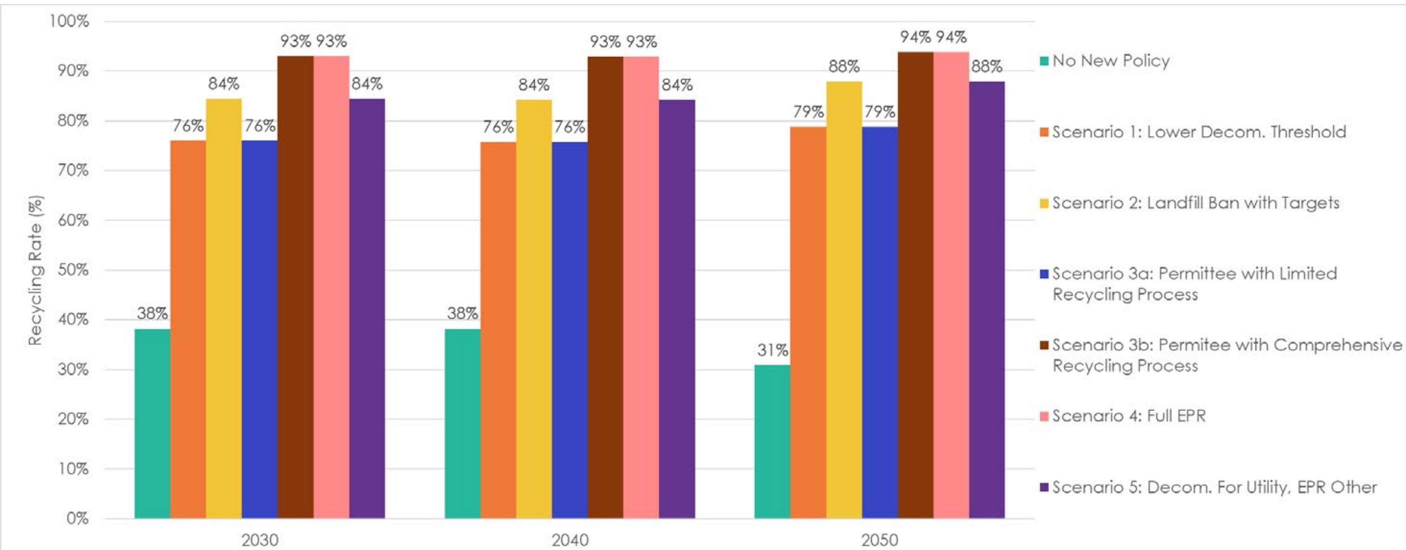
Figure 56. Tons of Solar PV Panel Components being Recycled Vs Ton of EOL Solar PV Panels



As seen in Figure 56, all policy scenarios have more tons recycled than the do-nothing scenario.

As seen in Figure 57, every policy scenario has a recycling rate that is at least 37 points higher than in the do-nothing scenario. A lower decommissioning threshold and a permittee funded model with limited recycling each have recycling rates at 76-79% for all years. The landfill ban with recycling targets, permittee pays with comprehensive recycling, full EPR, and decommissioning for utility, EPR for other scenarios have recycling rates between 84% and 93%. Note that the overall recycling rate does not vary significantly between scenarios with limited recycling and those with comprehensive recycling because the weight percent recovery may only differ by about 10 percent. However that additional 10 percent by weight includes most of the panel material value, which helps offset the higher cost to the permittee for comprehensive recycling. It is difficult to quantify the strategic/national security value or overall environment benefit of recovering and reusing these materials versus extraction and processing of virgin materials.

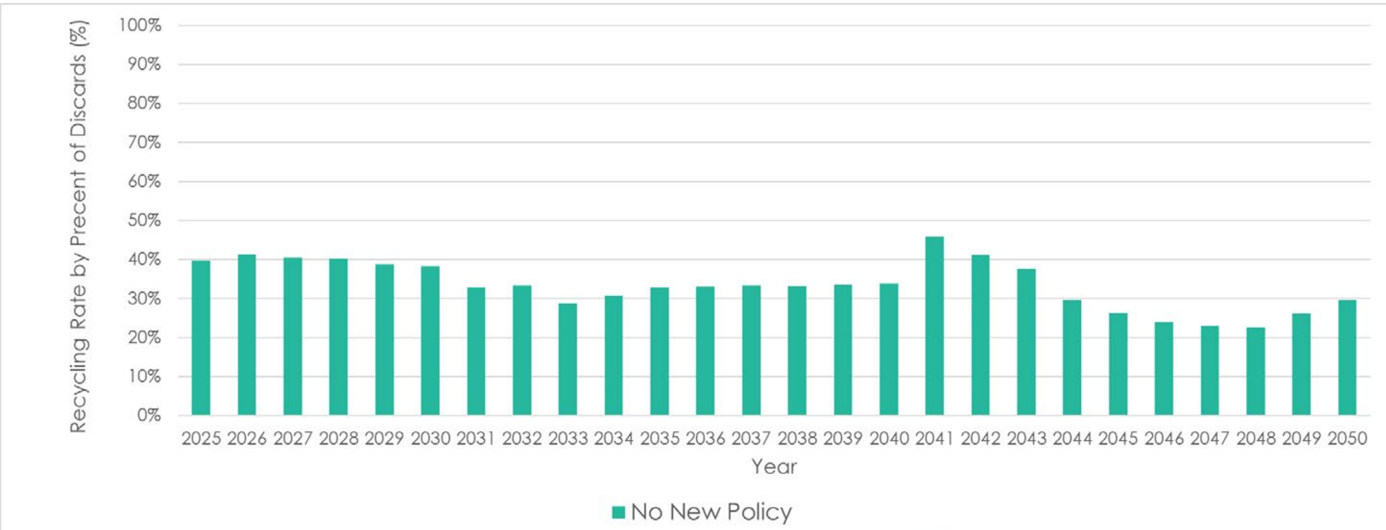
Figure 57. Recycling Rates in 2030, 2040 and 2050 under Different Scenarios



No New Policy Scenario:

Figure 58 shows the recycling rates calculated for the No New Policy Scenario. Rates for this scenario are highest in 2041 at ~46%, as a result of a large utility scale solar array projected to be coming offline.

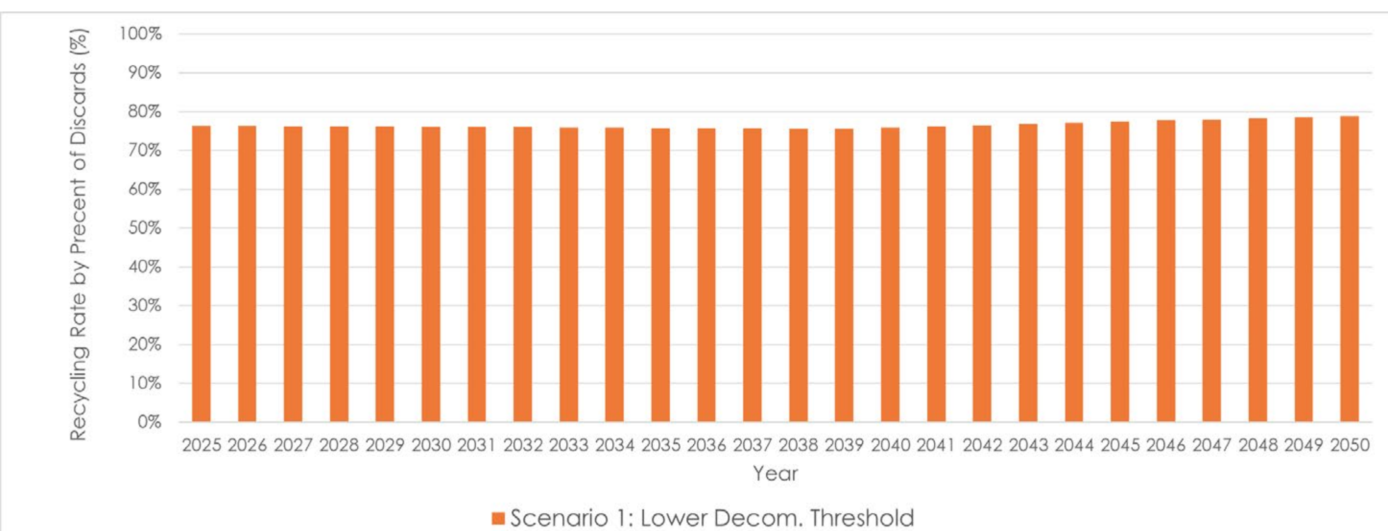
Figure 58. Recycling Rates by Percent of Discards – No New Policy Scenario



Scenario 1 – Lower Decommissioning Threshold:

Figure 59 shows the recycling rates calculated for Scenario 1 (Lower Decommissioning Threshold). In 2050, at their highest, these rates reach ~77%. This scenario has the same recycling rates as Scenario 3a (Permittee with Limited Recycling Process). This is a result of both scenarios only requiring a limited level of recycling. There will likely be little or no recovery/recycling of residential-commercial panels; CSGs will likely manage their panels since they will be covered by the new threshold.

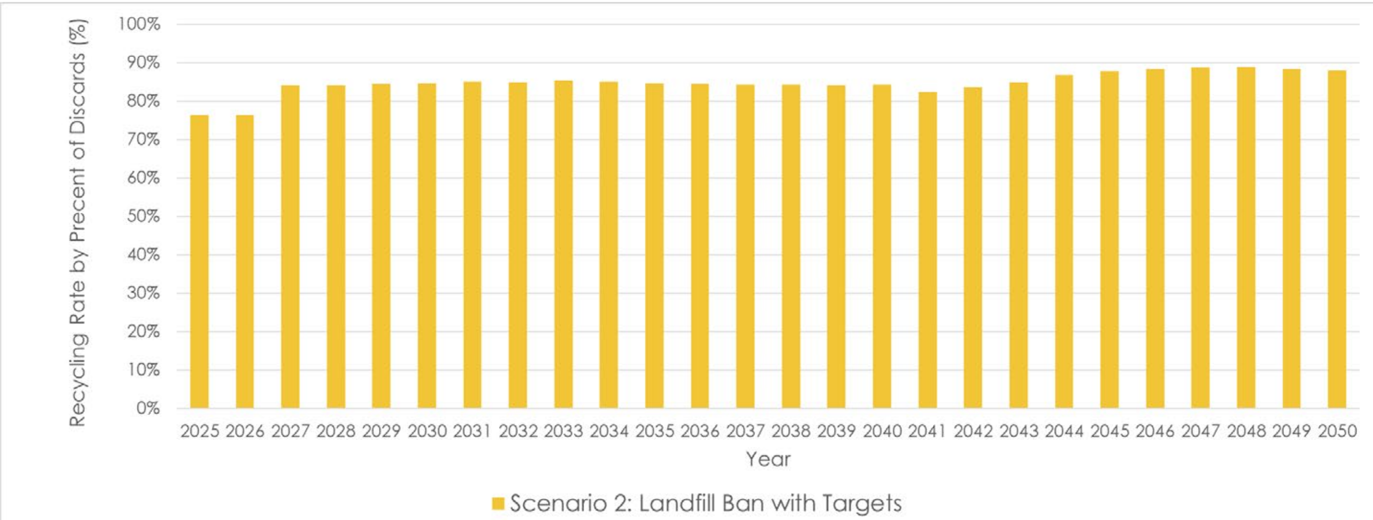
Figure 59. Recycling Rates by Percent of Discards – Scenario 1, Lower Decommissioning Threshold



Scenario 2 – Landfill Ban with Targets:

Figure 60 shows the recycling rates for Scenario 2 (Landfill Ban with Targets). Rates for this scenario range between 71% and 77%. From 2047 to 2050 these rates, at their highest, reaching ~77%. Recycling rates are higher in this scenario than in Scenario 1 and Scenario 3a as a comprehensive level of recycling is required except for utility panels with limited recycling.

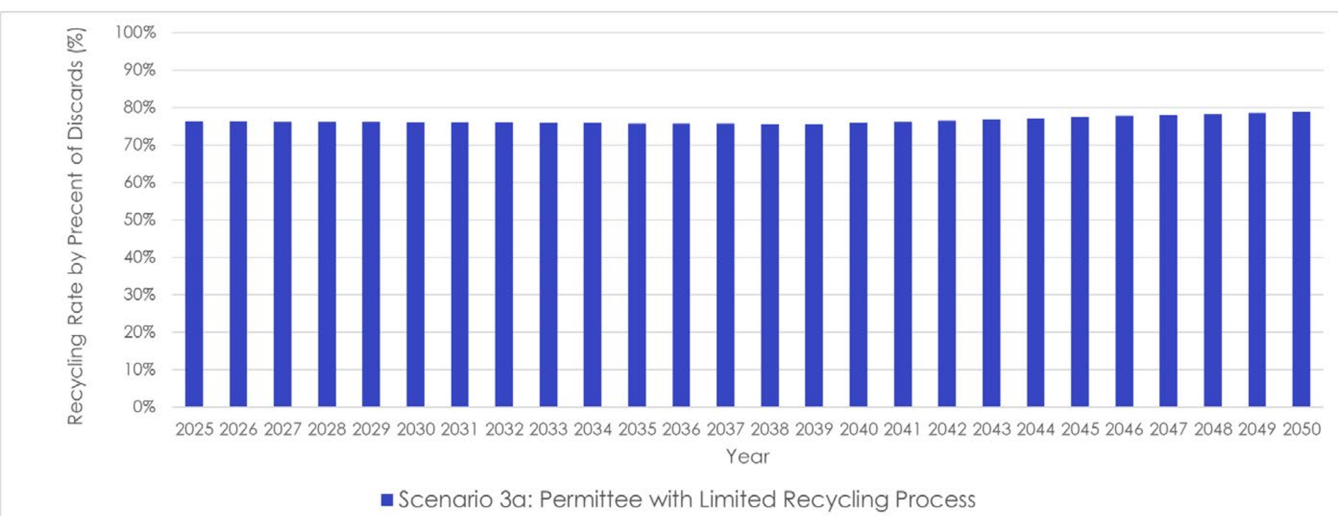
Figure 60. Recycling Rates by Percent of Discards – Scenario 2, Landfill Ban with Targets



Scenario 3a – Permittee with Limited Recycling Process:

Figure 61 shows the recycling rates for Scenario 3a (Permittee with Limited Recycling Process). In 2050, at their highest, these rates reach ~77%. This scenario has the same recycling rates as Scenario 1, Lower Decommissioning Threshold. This is a result of both scenarios only requiring a limited intensity/yield of recycling.

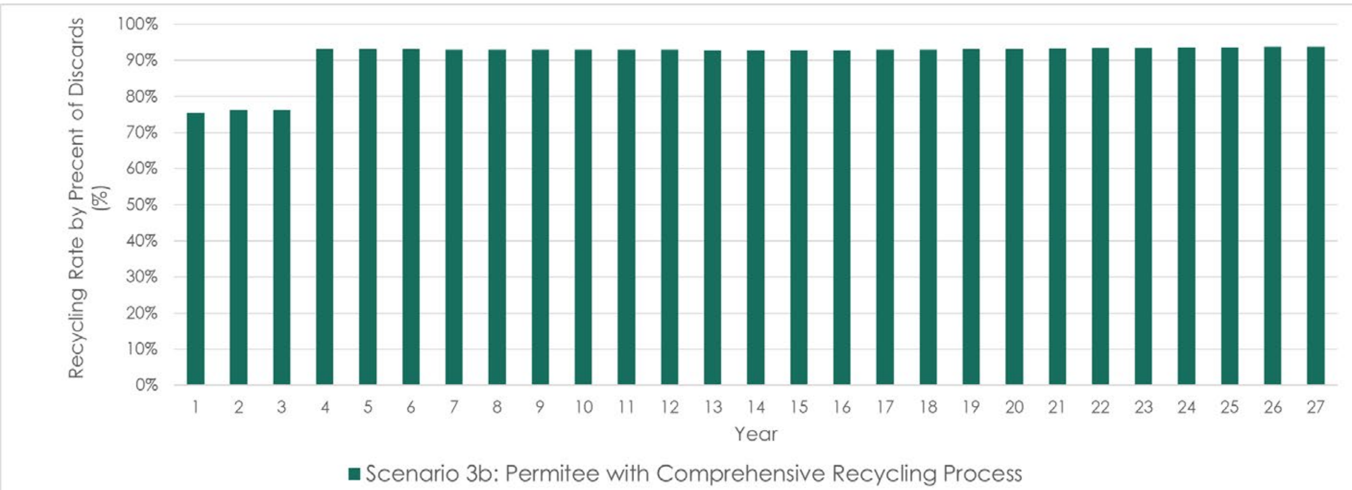
Figure 61. Recycling Rates by Percent of Discards – Scenario 3a, Permittee with Limited Recycling Process



Scenario 3b – Permittee with Comprehensive Recycling Process:

Figure 62 shows the recycling rates for Scenario 3b (Permittee with Comprehensive Recycling Process). In 2047 and 2048, at their highest, these rates reach ~89%. This scenario has higher recycling rates than Scenario 3a, as comprehensive recycling is required.

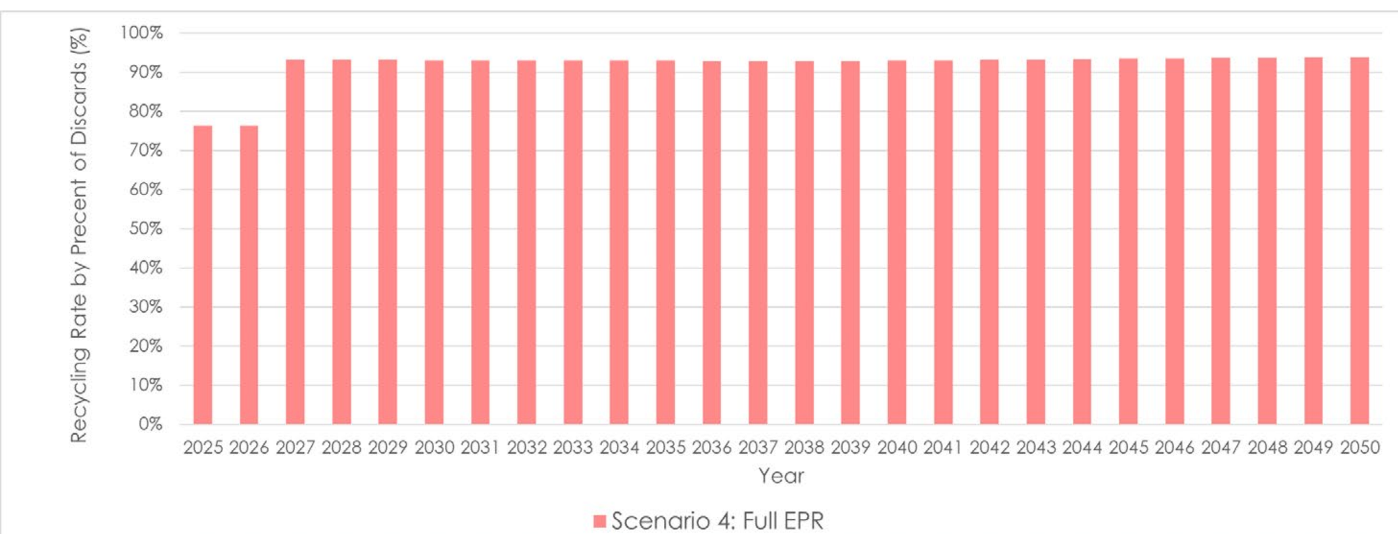
Figure 62. Recycling Rates by Percent of Discards – Scenario 3b, Permittee with Comprehensive Recycling Process



Scenario 4 – Full EPR

Figure 63 shows the recycling rates for Scenario 4 (Full EPR). Rates for this scenario range from ~76% to ~93% Full EPR requires recycling of collected solar PV panels, resulting in higher recycling rates compared to scenarios without those requires (Scenarios 1 and 3). This scenario also requires a comprehensive level of recycling.

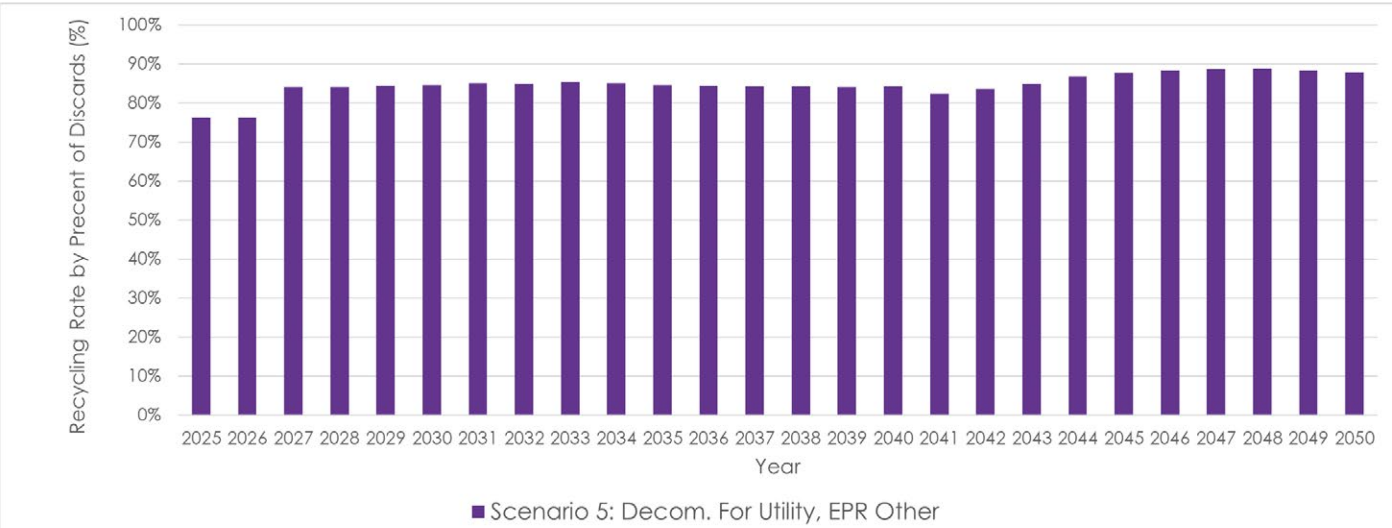
Figure 63. Recycling Rates by Percent of Discards – Scenario 4, Full EPR



Scenario 5 – Decommissioning for Utility, EPR for all other

Figure 64 shows the recycling rates for Scenario 5, Decommissioning for Utility, EPR for all other. Rates for this scenario ranges between ~75% and ~87%. This scenario requires a comprehensive level of recycling except for utility sector panels.

Figure 64. Recycling Rates by Percent of Discards – Scenario 5, Decommissioning for Utility, EPR for all other

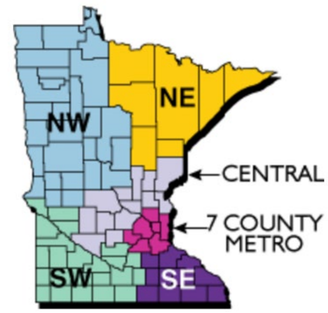


4.3 System Infrastructure and Technology Needs

Under each of the policy scenarios, there is expected to be additional infrastructure needs for Minnesota to properly manage EOL solar PV panels. The additional infrastructure would include:

- **Additional points of collection for small-scale solar installations.** To offer a convenient level of access for residential and commercial installations, consolidation centers would be necessary to receive de-installed panels from these sectors. These centers can take the form of either public/private depots dedicated to collecting solar PV panels, as is seen in the U.K.[45] Another option is for these bulking centers to be attached to installer hubs, such that there is an additional module on the installer warehouse dedicated to receiving and storing panels. France has 450 dedicated collection sites for solar PV panels.[46] If extrapolated to Minnesota's population, this would result in 38 sites statewide, while on a geographic basis that would extrapolate to about 180 sites. For modelling purposes, Eunomia has chosen to model one per county, which results in 83 bulking sites.

- **Recycling locations.** Throughout stakeholder engagement, there was discussion that residential and commercial (aka small-scale installations) could be sent to regional recycling locations throughout the state. These locations would not take in the larger scale, bulk utility panels. One smaller scale facility, Integrated Resource Technologies, has already begun accepting solar PV panels for recycling. Future small volume recyclers in the state may have to be co-located with other e-waste recycling, as the IRT facility takes streams other than PV cells. The exact tonnage of solar PV panels coming offline currently in the state is unknown, however the estimates from Section 3.2.3 suggest it may be 200 to 500 tons per year for years 2024-2026 (see Figure 34 and Table 18). If there were one small scale recycler per planning region in the state (see map at right), there would be six total facilities. Looking forward to 2050, five of these facilities could be smaller scale facilities receiving only commercial and residential panels. Each facility could receive and manage about 400 tons per year (~2000 tons total), similar to the estimated tons of solar PV panels currently coming offline in the state with one in-state recycler. One facility could be placed in Hennepin County (the most populous county within the state) and receive the larger scale installation (utility and CSG) EOL panels. In 2050, the five smaller regional facilities would each have a throughput of around 400-500 tons per year, while the Hennepin facility would have a throughput of around 12,000 tons per year serving utility and CSG customers.



4.4 Economic Development

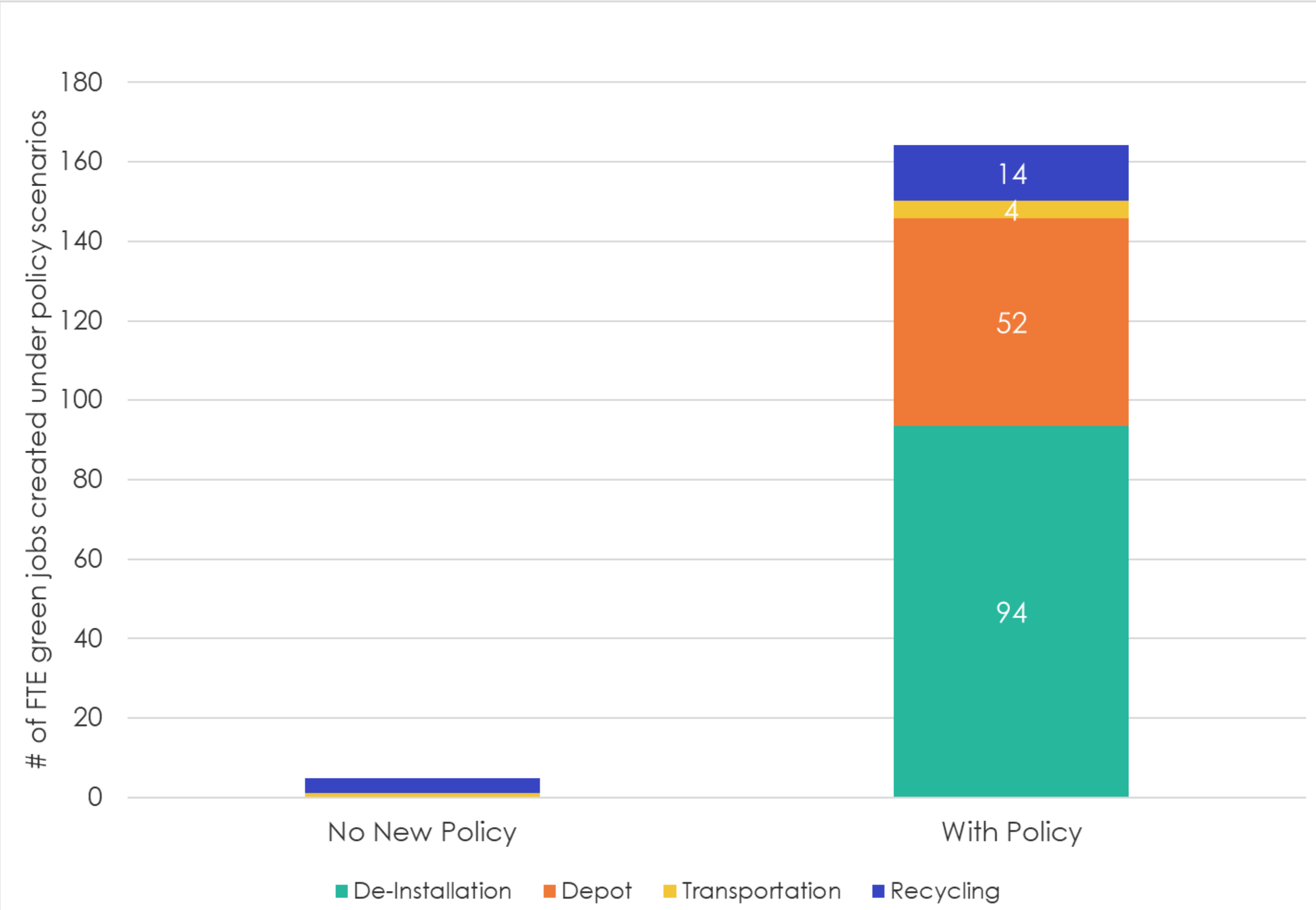
Eunomia estimated the number of jobs required to collect and recycle EOL solar PV panels in 2050. Eunomia did this by conducting a bottom-up, activity-based job estimation based on the time and person power it takes at each stage of recycling the panels. Eunomia used the key assumptions outlined in Table 46 to estimate the total number of jobs.

Table 46. Key Assumptions for Estimating Total Number of Jobs Required to Collect and Recycling EOL Solar PV Panels in 2050

Job Creation Step	Key Assumption	Source
De-installation	20 to 30 minutes per panel to de-install, depending on size of installation.	How Much Does It Cost to Remove Solar Panels? (2024) (homeguide.com)[47]
Depot Collection	6 FTE per 1000 tons/40,000 panels collected at a depot [0.07 FTE per 1000 panels collected].	Assuming an average of 2 people per Household Hazardous Waste (HHW) site in Minnesota. In 2022 48,000 tons of HHW were collected at 150 sites. 150 sites with 2 people each becomes 300 people, divided by 48 is 6 FTE per 1000 tons. Or 40,000 panels.
Recycling	0.03 FTE per 1000 panels recycled.	Based on SolarCycle employing 30 people,[48] and processing 1 million panels/year.[49]

Using the job intensities in Table 46 and the total tonnage of solar PV panels recycled in 2050, Eunomia estimated jobs figures created under policy as shown in Figure 65. Though the number of solar PV panels recycled varies under each policy scenario, the number of jobs estimated does not vary. This is because while the policies and recycling methods vary by scenario, each scenario is designed to collect 100% of solar panels which reach their end of life. The labor for the overall collection system and infrastructure remains similar across scenarios, while the end-of-life requirements and program costs vary.

Figure 65. Green Jobs in 2050 Under Policy Versus No New Policy



A total of 164 direct FTE green jobs are created under the policy scenarios. This is contrasted with 5 FTE jobs created under the No New Policy Scenario.

Most jobs are created during de-installation, as it is the most time-consuming part of the process. This is followed by depot jobs as there must be employees stationed at every depot who spend at least some of their time on solar PV panel recovery.

4.5 Environmental Justice Impacts

How solar PV panels are managed at the end of their life cycle has both positive and negative environmental justice (EJ) implications for communities, including Tribal communities, in Minnesota. The following section outlines key takeaways about environmental justice considerations from stakeholder interviews and summarizes the extent to which the solar EOL policy scenarios modelled in this study can directly address those environmental justice concerns.

4.5.1 Environmental Justice Findings from Stakeholder Interviews

The Minnesota Pollution Control Agency (MPCA) is committed to environmental justice (EJ), the fair treatment and meaningful involvement of all people in the development, implementation, and enforcement of environmental laws, regulations, and policies, and to ensuring that no decisions disproportionately burden environmental justice communities. The agency's Environmental Justice Framework, developed in 2015 and updated in 2022, identifies strategies to ensure that environmental justice communities are informed about, engaged in, and have meaningful input into permitting processes, decisions about materials management facilities in their communities, and materials management policies. The agency strives to put community benefit and quality of life at the center of environmental reviews and remediation actions and encourages facilities to be in ongoing and transparent communication with the communities in which they operate. These efforts are ongoing and there remains much work to be done to eliminate long existing disparities in the environmental impacts borne by low-income neighborhoods and communities of color, including indigenous communities. Therefore, MPCA also considers and seeks to address EJ concerns in the development of new materials management laws and regulations.

This study included an examination of the potential for each solar EOL policy scenario to address EJ issues related to solar PV panel end-of-life management, which would augment existing policies that already address these concerns to some extent. As part of PSI's stakeholder consultation process (see Section 2.3), interviewees were asked about the potential benefits and negative impacts of solar PV panel recycling on Minnesota communities, including environmental justice communities. A full list of interviewees is included in Appendix A.2.0. Five considerations affecting the impacts on communities were raised during stakeholder interviews:

(1) Responsible End Markets

(2) Occupational Health and Safety

(3) Emissions from Transportation

(4) Community Engagement in Facility Siting and Communications about Ongoing Operations

(5) Materials Recovery and Recycling Should be Maximized

1. **Solar EOL Policy Should Ensure Use of Responsible End Markets**

   Nearly all interviewees expressed a strong interest in ensuring the responsible handling and disposition of solar PV panels to end markets with protective environmental and health and safety regulations, where materials would be handled safely and recovered to the highest and best use. All stakeholders interviewed were opposed to landfilling and incineration of solar PV panel waste and supported a landfill ban on solar PV panels.

   Minnesota's packaging EPR law (Minn. Stat. § 115A.1441, Subd. 31) Packaging Waste and Cost Reduction Act; Statute 115A.144-115A.1463), requires disposition of materials to a "responsible market." The statute defines a responsible market as one where materials are handled per Minnesota's waste hierarchy, in a manner that protects the environment, minimizes risks to public health and worker health and safety, complies with all applicable laws, and minimizes adverse impacts to environmental justice areas. If this responsible end market standard were adapted to address solar PV panels, the policy should modify the "waste hierarchy" criteria to ban landfilling and incineration, similar to the ban on landfilling and incineration of electronics, since doing so would pose a threat to public health and the environment and disproportionately impact environmental justice communities.

Minnesota's packaging EPR law also requires a third-party certification that the program and its service providers are meeting the responsible market standard. Nearly all stakeholders recommended a third-party certification to verify that solar PV waste is sent to such an end market. Some stakeholders suggested that this certification could be modelled on existing requirements in Minnesota's electronics EPR regulation, Section 115A.1318, that stipulates only electronics recycled by a registered recycler, which is certified by an ANSI-ASQ National Accreditation Board-accredited third-party certification body (in practice e-Stewards or R2 certification), may be counted towards the manufacturer's minimum recycling obligation.

Interviewees also expressed interest in ensuring that panels were not abandoned or illegally dumped, leaving communities with an eyesore, possible exposure to toxic materials, and the costs of disposal or recycling. Installers of large installations noted that they would support regulations for ensuring that responsible and proper recycling and reuse occurs. One recycler suggested manufacturers be required to furnish information on the toxicity of their panels, ideally at regular intervals (e.g., annually) through a centralized and publicly available central clearinghouse.

2. **Solar EOL Policy Should Ensure the Occupational Health and Safety of Solar Recycling Workers**

The academic researcher interviewed noted three primary occupational safety concerns related to solar system recycling: injury or death from glass and metals, injury or death from electric shock, and exposure to toxics such as lead. The processing of solar PV panels involves handling glass and metal, as well as electrical equipment. These materials can be dangerous or deadly to workers if there are inadequate safety precautions in place. It is essential that facilities processing solar PV panels have robust safety protocols and procedures, including use of appropriate protective gear and training and ongoing education about how to handle materials to prevent electric shock and injury.

Training should also address how to handle clothing contaminated with lead and other toxins, so that workers are not bringing toxic materials home to their families. A portion of solar cells are covered in a lead metallization paste, which workers are exposed to during processing. There is a push for lead-free manufacturing and the amount of lead per cell is going down with each generation of solar PV panels. However, panels increasingly use double-sided cells, so although the amount of lead in each cell is going down, total lead in panels is increasing. Workers may also be exposed to cadmium and lithium-ion batteries, which pose fire hazard.

Although "living wage" provisions did not come up in stakeholder interviews, one interviewee did note that recycling workers are often low-wage workers and part of EJ communities. Minnesota's packaging EPR law requires a living wage for employees of program service providers and could be a model for inclusion in the EOL solar PV policy. The statute (Minn. Stat. § 115A.1441, Subd. 21) defines a "living wage" as "the minimum hourly wage necessary to allow a person working 40 hours per week to afford basic needs."

3. **Emissions from Transportation Should Be Minimized**

Environmental justice communities are overburdened by the impacts of carbon emissions from traffic and industrial facilities that result in higher rates of asthma and other health issues. The academic researcher interviewed suggested that the impacts of transportation associated with solar PV panel recycling should be considered when developing policies and implementing solar PV panel recycling programs. For example, EOL solar PV policy could incentivize the use of Minnesota-based or regional recycling facilities to limit transportation distance and emissions. Alternatively, complementary incentive programs could promote the adoption of zero emission medium and heavy-duty trucks. The state of Minnesota submitted over 350 project ideas for the U.S. EPA's Climate

Pollution Reduction Grants (CPRG) and includes a program (DRIVE for $39 million) focused on incentivizing the roll out of zero emission medium and heavy-duty trucks. Leveraging similar efforts to support the infrastructure to transport EOL solar PV panels could alleviate challenges tied to the transportation burden within EJ communities.

4. **Communities Should be Engaged Early and Often in the Siting, Permitting, and Oversight of Solar PV Recycling Facilities**

When facilities are located within communities that already bear a high environmental burden – due to high traffic volumes, reduced tree cover, flooding, high asthma rates, and other environmental disparities – adding another facility would further compound the environmental impacts on the community. Solar PV panels, batteries, and ancillary equipment contain per-and polyfluoroalkyl substances (PFAS), and other materials that will need to be managed to protect air, water, and land resources in communities where solar PV recycling facilities are operating, particularly in those that already bear the burden from cumulative impacts.

Stakeholders interviewed for this study emphasized the importance of ensuring that the health of no community be sacrificed – or overburdened – by solar PV panel recycling. As solar PV recycling facilities are established in Minnesota in response to demand for EOL solar PV management, MPCA should consider ways to augment existing policies (see below) and regulation governing siting of facilities, permitting processes, ongoing regulatory oversight, and community engagement. For example, the U.S. EPA provides guidance on how to use its EJ Screen tool when siting renewable energy facilities and other industrial facilities. A new policy could require the use of the EJ screening tool to examine environmental justice issues related to locations being considered for solar recycling facilities.

Permitting processes for facilities built with funding from MPCA are already required to conduct a community engagement process. A solar recycling policy could reinforce and expand those regulations. For example, a central coordinating body of a permittee-funded or EPR program could be required to send EOL solar PV panels only to recycling facilities that conduct a facilitated community engagement process when they site a new facility and that foster ongoing communication with the communities in which they are sited. Additionally, many recent EPR laws enacted in the U.S. require the formation of a multi-stakeholder advisory board, which include representation from environmental justice communities. This advisory board provides input into the program plan (including operations, such as facilities where panels are sent, and education and outreach plans) and advises the state agency on plan and annual report approval and oversight issues. The advisory board provides all program stakeholders, including environmental justice communities, with more opportunities for feedback.

Working with communities and EJ advocates early in the siting process can help ensure that facilities are operating to the highest environmental health standards and secure buy-in from the community for the facility. Early engagement also helps establish transparent and ongoing communications, which MPCA encourages all solid and hazardous waste management facilities to foster with the communities where they are sited. These communications should include updates on ongoing operations, including safety records, the types and level of emissions from the facility, emission mitigation strategies in use, and incidents and regulatory reviews (if any).

5. Materials Recovery and Recycling Should be Maximized

Not recycling solar PV panels and system components would result in significant loss of valuable materials and potentially lost jobs. Solar PV panel frames are usually made of aluminum, which can be infinitely recycled and valuable, while virgin aluminum extraction is very carbon intensive. Solar PV panels also contain silver; the industry is projected to demand 20 percent of global sliver supply by 2027.[50] Recovering and recycling that silver would reduce demand for virgin material and increase supply for a high-demand commodity. The purified silicon in solar PV panels ought to be recovered and recycled, as should the batteries and inverters that are part of every solar system. A lot of mining and the detrimental impacts of mining could be avoided by recovering the aluminum, silver, silicon, and other materials that make up solar energy systems. A "no new policy" scenario would therefore be the least environmentally preferable approach.

4.5.2 Potential Environmental Justice Impact in Modeled Scenarios

The modeled policy approaches for EOL solar PV, if implemented, would interact with and/or lay atop existing laws and regulations at the federal, state, and local levels. It is important to note that the policy options under consideration would be established for the State of Minnesota and would not govern what happens on sovereign Tribal lands.

The following existing regulations apply to various aspects of solar system waste in the State of Minnesota:

General

- Minnesota Environmental Policy Act, Section 116D.03 Section 3, which requires all government departments and agencies to continuously strengthen environmental planning and management programs, integrate national, social, and environmental sciences into planning and decision-making, establish ways to ensure environmental information is given as much weight as economic and technical information in decision-making, support and maximize intergovernmental cooperation to address environmental challenges, make environmental information available, gather data to inform planning and development of resource projects, and conduct research to address pollutants of concern.

- Minnesota Environmental Policy Act, Section 116D.04, which requires the government to provide an environmental impact assessment for projects that will have an impact on the environment, which serves as a guide in issuing, amending, and denying permits and carry out other government responsibilities related to avoiding or minimizing adverse environmental impacts and restoring and enhancing environmental quality.

- For Responsible End Markets

    - State decommissioning requirements, which currently apply to installations larger than 50 MW, require removal of system waste at end-of-life and return of the land to its original condition, while local laws require financial assurances (e.g., insurance coverage, certified funds, cash escrow, or a letter of credit bonds) and may require decommissioning for smaller installations, with variation across communities.

    - No regulations currently ensure that solar PV panel waste is sent to responsible end markets – facilities and regions where there are adequate environmental, health, safety, and labor regulations.

For Occupational Health and Safety

- Federal (CFR 29) and state (Chapter 182) health and safety standards require training, safety equipment, and safety procedures appropriate to business operations and would cover solar recycling facilities.

For Community Engagement in Facility Siting

- The Minnesota Waste Management Act, Chapter 115A, provides for a waste management capital assistance program, described in Section 115A.51. Under section 115A.51(8), any applicant receiving agency funds must have "reviewed the project's impact on environmental justice areas, conducted stakeholder engagement, and assessed community input" to receive funding for new facilities. Section 115A.51(7) also requires that the applicant evaluate the project's environmental impact on climate change, including greenhouse gas emissions. However, neither of these regulations apply to privately funded projects or local projects conducted without capital assistance program funds.

- Local zoning policies and procedures govern the siting of facilities and may with variability across jurisdictions seek community input.

A breakdown of how each policy scenario could potentially address EJ concerns is provided below.

No new policy: This scenario does not address responsible markets, occupational health and safety, transportation emissions, and community engagement in solar recycling facility siting and operations.

Scenario 1 - Decommissioning for all grid-tied installations (e.g., <1 MW): This policy would address responsible end markets if the statute requires the use of third-party certified recyclers for all solar PV panels subject to decommissioning. This certification could be modelled on requirements in Minnesota's electronics EPR regulation, Section 115A.1318. For solar installations under the decommissioning threshold (e.g., < 1 MW), this scenario would do no more than current regulations to address responsible markets, occupational health and safety, transportation emissions, or community engagement.

Scenario 2 - Landfill ban with targets: This scenario does not address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement. However, it does prevent environmental contamination of land and water resources.

Scenario 3 - Permittee / Owner Pays: This policy assumes a central body that would have control over program operations. Therefore, the statute could include provisions that address EJ concerns. For example, the policy would address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement if the statute included provisions similar to Minnesota's packaging EPR law. The packaging EPR law requires a living wage for all program workers and third-party certification that materials are sent to a market where materials are handled per Minnesota's waste hierarchy, in a manner that protects the environment, minimizes risks to public health and worker health and safety, complies with all applicable laws, and minimizes adverse impacts to environmental justice areas. Alternatively, this scenario would more narrowly address responsible end markets by adopting provisions similar to Minnesota's e-waste regulation. Additionally, because this scenario assumes EOL funding would be secured at purchase or installation of the panels through a consumer fee, this policy would do more to prevent abandoned and illegally dumped EOL solar PV than no new policy or scenarios 1 and 2.

Scenario 4 - Full EPR: Similar to the permittee scenario, a Full EPR model has a central body – a producer responsibility organization – which is accountable for the program. A Full EPR policy would address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement by including policy provisions similar to Minnesota's packaging EPR law. The packaging law requires a living wage for all program workers and third-party certification that materials are sent to a market where materials are handled per Minnesota's waste hierarchy, in a manner that protects the environment, minimizes risks to public health and worker health and safety, complies with all applicable laws, and minimizes adverse impacts to environmental justice areas. Alternatively, the Full EPR policy would address responsible markets more narrowly by requiring the use of third-party certified recyclers as in Minnesota's electronics EPR law. Additionally, because EOL funding would be secured upon purchase of the panels, this policy would do more to prevent abandoned and illegally dumped EOL solar PV than no new policy or scenarios 1 and 2.

Scenario 5 - Decommissioning for utility, Full EPR otherwise: For the decommissioning portion, the regulation would further address responsible end markets by requiring use of third-party certified recyclers, as in Minnesota's e-waste regulation. It would do no more than current laws and regulations to address occupational health and safety, transportation emissions, and community engagement. The Full EPR portion would address responsible end markets, occupational health and safety, transportation emissions, and EJ community engagement by including provisions similar to Minnesota's packaging EPR law, as described in scenarios 3 and 4. Alternatively, the Full EPR policy would address responsible markets more narrowly by requiring use of third-party certified recyclers as in Minnesota's electronics EPR law. Additionally, because EOL funding would be secured at purchase or installation of the panels, this policy would do more to prevent abandoned and illegally dumped EOL solar PV than no new policy or scenarios 1 and 2.

Appendix

A.1.0 MnSEIA Survey

The below survey was distributed to MnSEIA members via their weekly newsletter in July 2024.

Survey Title: **Contribute to a study assessing policy options for a statewide system for solar PV end-of-life management**

Eunomia Research and Consulting, Inc. was hired by the Minnesota Pollution Control Agency to prepare a report under [2023 Session Laws Chapter 60/HF2310 (search for 'Recycling and Reusing Solar Photovoltaic Modules and Installation Components')](). As part of the research process, Eunomia is inviting MnSEIA members to respond to a short survey to help inform the analysis of removal and end-of-life management. All responses will be held in confidence by Eunomia and will not be shared with MPCA. While the data may be used to inform the study, it will not be attributed to its providers. Thank you for your time. Responses are due by July 26, 2024.

Question 1: When your company needs to remove and manage panels that have been installed, do you (check all that apply):

- ☐ Store panels for minimum quantity to ship
- ☐ Reuse
- ☐ Recycle
- ☐ Landfill disposal in Minnesota
- ☐ Landfill disposal outside of Minnesota
- ☐ Hazardous waste disposal outside of Minnesota

Question 2: Of your panels that have reached their end-of-life over the past ten years, what is the estimated percentage of solar panels that have gone to each of the pathways below?

- ☐ Reuse
- ☐ Recycling
- ☐ Landfill disposal in Minnesota
- ☐ Landfill disposal outside of Minnesota
- ☐ Hazardous waste disposal outside of Minnesota
- ☐ Other end-of-life pathways (please note what the pathway is)

Question 3: Can you estimate the quantity of solar panels you've managed at end-of-life each year over the past ten years (pounds or number of panels)?

- ☐ In 2014
- ☐ In 2015

- ☐ In 2016
- ☐ In 2017
- ☐ In 2018
- ☐ In 2019
- ☐ In 2020
- ☐ In 2021
- ☐ In 2022
- ☐ In 2023

Question 4: For each option below, please provide the estimated cost per panel along with transportation costs associated with each pathway:

- ☐ Deinstallation/removal of the panel
  - Estimated cost per panel
- ☐ Reuse
  - Estimate cost or value per panel
  - Transportation costs
- ☐ Recycling
  - Estimate cost per panel
  - Transportation costs
- ☐ Landfill disposal in Minnesota
  - Estimate cost per panel
  - Transportation costs
- ☐ Landfill disposal outside of Minnesota
  - Estimate cost per panel
  - Transportation costs
- ☐ Hazardous waste disposal outside of Minnesota
  - Estimate cost per panel
  - Transportation costs
- ☐ Hazardous waste disposal outside of Minnesota
  - Estimate cost per panel
  - Transportation costs

- Other end-of-life costs (please note what the cost is)

Question 5: [OPTIONAL] Please add your contact information below if you are happy for Eunomia to contact you with clarification or additional questions if necessary.

- Name
- Organization
- Email

A.2.0 Interview Key Findings

The Product Stewardship Institute conducted multiple 1-hour interviews with EOL solar panel stakeholders in Minnesota and the United States. Interviewees were asked about the need for EOL solar panel policies, the policy scenarios being modeled for Minnesota, potential benefits and negative impacts of solar panel recycling on communities including environmental justice communities, and any data or insight they may have for the modeling outputs. Below is the list of the interviewees:

Interviewees:

- Dawn Timm, Niagara County, New York, Local Government
- Doug Kobold, California Product Stewardship Council, Local and State Government
- Adam Sokolski, EDF Renewables, Solar Installer
- Logan O'Grady, Minnesota Solar Energy Association, Industry Association
- Curtis Zaun, Minnesota Solar Energy Association, Industry Association
- Suzanne Steinhauer, Minnesota Department of Commerce, State Government
- Nick Cain, SolarCycle, Recycler
- Martin Pochtaruk, Heliene, Manufacturer
- Pascal Caputo, First Solar, Manufacturer and Recycler
- Karen Drozdiak, First Solar, Manufacturer and Recycler
- Nels Paulsen, Conservation Minnesota
- James Lehner, Conservation Minnesota
- Dustin Mulvaney, San Jose University
- Andrew Boyd, Mille Lacs Band of Ojibwe
- Charlie Lippert, Mille Lacs Band of Ojibwe
- Andrea Zimmerman, Prairie Island Indian Community
- Brian Ross, Great Plains Institute
- Maggie Schuppert, CURE Minnesota
- Hudson Kingston, CURE Minnesota

Key takeaways regarding the policy mechanisms modeled for Minnesota and community level impacts are included in section 2.2.1 and section 4.5 respectively. Additional interview insights are summarized below.

Need for End-of-life Solar PV Panel Policy

All interviewees agreed that there is a need to address the future volume of solar PV panels that will need EOL management. Solar manufacturers, installers, recyclers, and industry associations did not feel that there is an urgency to implement a policy in the near term except for a landfill ban. Solar installers, recyclers, and industry associations were also unsure if the 20- to 25-year life expectancy for panels was a reasonable estimate as many new panels have 30 plus year warranties, and it is unlikely that homeowners will replace panels unless there is a dire need (hail damage) or a significantly more efficient and cost-effective panels on the market. Local and state officials, an environmental group, an academic researcher, and officials from two tribes in Minnesota felt that policies should be put in place now instead of waiting for the volume of EOL panels to grow. Citing lessons learned from past and current events, one interviewee from a tribe in Minnesota described the large stockpiles of old electronics they cleared from abandoned buildings when they first began recycling electronics, and several environmental nonprofit stakeholders cited a wind turbine junkyard, which was featured in a recent Star Tribune article, that materialized in a small Minnesota town south of Minneapolis as examples of the risks of not planning for end-of-life management of solar PV panels.

Policy Scenarios

Interviewees' thoughts on the policy scenarios varied by stakeholder group and by the solar PV panel sector to which the policies would apply (i.e., residential vs. utility). State and local government officials generally agreed that a permittee-funded or an EPR approach would be needed to create a program to address EOL of panels, while the academic researcher favored the EPR approach, since manufacturers reap the most profit and because installers/permittees are economically squeezed in the current market. Manufacturers, installers, recyclers, and industry associations believed that requiring decommissioning plans and enforcing a landfill ban with recycling targets would be effective. The interviewees from two tribes in Minnesota noted that they are not subject to Minnesota state law and their participation in any program would be voluntary. One tribe finds the advanced recycling fee they assess for electronics recycling to be effective and suggested it could be a policy model for solar recycling.

Most of the interviewees acknowledged that significant differences in economics and logistics between deinstalling and recycling utility-scale solar arrays and smaller rooftop arrays may warrant different end-of-life management approaches. Utility-scale projects have more EOL value and are more cost efficiently collected and transported than the smaller, distributed net-meter installations that have a higher cost to value ratio. Manufacturers, installers, recyclers, and industry associations agreed that a fee-based program may be needed to enable EOL management for residential/rooftop solar PV panels. When asked directly about a hybrid model, whereby decommissioning would be required for utility-scale arrays and an EPR model would be used for smaller rooftop systems, the academic and environmental nonprofit interviewees expressed support for exploring this approach.

Decommissioning

Manufacturers, installers, recyclers, and industry associations were supportive of the use of decommissioning plans with financial assurance tools that allow the installation owner to build up the needed funds over the life of the installation. Some nonprofit organizations also were supportive of the use of decommissioning plans with financial assurance tools, provided the threshold for decommissioning was lowered; suggestions included 10 MW, 5MW, and 1 MW. Interviewees from two tribes in Minnesota expressed interest in reevaluating and reducing the megawatt threshold requirement for decommissioning to cover more installations. They also suggested several solar installations near each other and/or owned by one entity might be combined for the purposes of meeting the minimum megawatt threshold for decommissioning. One tribe interviewed owned two solar arrays, one 3.2 KW and the other 6 KW, and has a long-term lease on a 3 MW array; the other also has a solar array that uses panels from Heliene. State government officials expressed concerns with lowering the threshold from 50 MW to require more projects to be covered by state decommissioning requirements instead of local government requirements. Local governments in Minnesota may be reluctant to give up their ability to determine decommissioning requirements. Most interviewees agreed that decommissioning plans/requirements would not be an effective policy for managing residential/roof-top solar PV panels.

Landfill Ban with Recycling Targets

All interviewees agreed that a landfill ban with recycling requirements was needed and would be needed to supplement other policy scenarios as well. Installers reported that most large project installers were requiring recycling in their decommissioning plans already but were supportive of ensuring a requirement for all installations. Interviewees expressed that a landfill ban would need regulations and enforcement to ensure EOL panels are not shipped out of state to be landfilled.

Permittee and Ratepayer Funded

Manufacturers, installers, recyclers, and industry associations did not feel that a fee was needed to cover the cost of installations that already required a decommissioning plan, but it may be needed to fund a program for residential/rooftop panels. One tribe interviewed noted that their advanced recycling fee for electronics works well and could be a model for solar recycling. State and local government officials agreed that a fee-based program could work for residential/rooftop solar PV panels but were skeptical that a utility rate to fund the program would be politically feasible. The environmental nonprofit interviewees preferred to see no cost burden for solar recycling on individual households and small businesses. However, they also noted that because the utility commission is closely monitored by their organization and scrutinized by the public, they would not expect ratepayers in Minnesota to be overcharged. They noted, however, that it would be politically problematic, as any increased costs would be blamed on policy makers supporting renewable energy. Another nonprofit organization pointed out that largely rural, off-grid solar arrays would be free-riders in a ratepayer-funded system, since they are not ratepayers. The academic researcher interviewed discouraged placing additional costs on installers, since installers are economically squeezed in the market.

Extended Producer Responsibility

State and local government officials currently implementing EPR programs for solar PV panels reported difficulty with getting solar PV panel manufacturers to register for the program. Their programs were moving down the list of responsible parties to distributors, project developers, and installers to fund the program. Manufacturers, installers, recyclers, and industry associations were not supportive of an EPR approach. The academic and environmental nonprofit interviewees were all supportive of an EPR approach, if not for all solar, then for residential/rooftop installations. Manufacturers, installers, recyclers, and industry associations were not supportive of an EPR approach.

Modeling Outputs

Interviewees did not provide additional data sources outside of information already available from the National Renewable Energy Laboratory (NREL). Interviewees expressed that the low volume of panels currently needing EOL management and the long-life expectancy for panels make it difficult to model the future EOL generation, EOL costs, and any economic impact from EOL activities for panels.

When asked about potential benefits and negative impacts of solar system reuse and recycling on environmental justice communities in Minnesota, interviewees noted costs of both solar installation and recycling, responsible end markets, occupational safety, community impacts, and upstream design changes as policy factors that should be modeled and considered in the study. The academic researcher interviewed noted that catastrophic events such as hailstorms, which are not accounted for in NREL’s model, sometimes cause sudden, short-term increases in solar system waste. All policy scenarios should consider what would happen if suddenly a large installation needed EOL management before the end of its expected life.

Reuse and Recycling Costs and Values

Installers and recyclers indicated that the reuse market for panels is volatile and that reused panels will continue to have difficulty competing with the rollout of better and cheaper new panels. Reuse would be more likely to come from the decommissioning for large solar utility installations as these solar PV panel owners have incentives to repower their projects before the panels lose value in the reuse market. Even reused panels from utility installations may struggle to find value in the reuse market. Installers and recyclers reported that the cost for recycling panels from large installations was on the lower end of the NREL estimates ($15-45) and that the cost of recycling was expected to decrease a few percentage points year over year. Recyclers reported that transportation to a recycling facility creates most of the variability in the pricing they offer. Recyclers also indicated the hazardous waste regulations for the transportation and processing of panels impacted the cost of recycling.

Employment and Economic Impacts

It was unclear to interviewees what kind of impact the EOL management of solar PV panels and the policy scenarios could have on job growth in Minnesota. Installers reported that there is still a need for labor for solar PV panel installation and that decommissioning of panels would likely rely on the same labor force. Recyclers reported that the volume of panels needed to be recycled was too low in the upper Midwest to merit consideration for a solar PV panel recycling facility. Existing electronics recyclers in Minnesota may benefit from handling solar PV panels but it was unclear if they would need additional staff to accommodate this waste stream. One tribe interviewed, which operates an electronics recycling facility, is just starting to examine the opportunities of recycling solar PV panels and system components. Recyclers explained that even with a higher volume of panels in the future, facilities that recycled the solar PV panel glass would likely continue to be sited in the southwest and southeast due to the larger volume of panels in those areas.

Net Costs for a Program

Manufacturers expressed concerns that the permittee funded and EPR policy scenarios may put the costs of the program on US solar PV panel manufacturers and, in general, drive up the costs for new panels. Interviewees from two tribes in Minnesota also expressed a concern that costs imposed on manufacturers would be passed down to consumers, making the cost of solar arrays less affordable. The academic researcher interviewed suggested this concern may be unfounded; the European Union established EPR for solar EOL management and solar systems are less expensive to install in the EU than in the US. This suggests that recycling costs, which are estimated to be 5% of total solar system costs, are not driving overall system costs. All interviewees believed that decommissioning plans with financial assurances could manage the EOL costs for large solar PV panel installations, but that a landfill ban and recycling requirements would be needed to overcome the much lower cost of landfilling panels. Interviewees agreed that EOL management for residential/rooftop panels could be more costly per panel than utility installations, because of lower overall system value and higher collection costs per panel. Several interviewees suggested that managing residential/rooftop panels cost efficiently would require a network of collection points convenient to residential solar installers that could store and generate enough panels for cost-effective transportation to a recycling facility. Costs for a program may also vary depending on how the glass from panels is required to be processed. A program that allows the glass to be ground into a cullet and used in applications without further processing will cost less than a program that requires advanced recycling of the glass in which the glass is further processed to remove metals.

Responsible End Markets

Many interviewees, including recyclers, the environmental nonprofit, the academic researcher, and tribes interviewed all expressed a strong interest in policy options that would ensure the responsible handling and disposition of solar to end markets where materials would be handled safely and recovered to the highest and best use. Installers of large installations noted that they would support regulations for ensuring that responsible and proper recycling and reuse occurs. One recycler suggested manufacturers be required to furnish information on the toxicity of their panels.

Occupational Safety

The academic researcher interviewed noted three primary occupational safety concerns related to solar system recycling: glass, electronic shock, and lead and other toxics. Policies and protocols, including using appropriate protective gear, should be in place to protect workers from injury from glass and sharp metal. Training and ongoing education about how to handle materials to prevent electric shock should also be required. Training should also address how to handle clothing contaminated with lead and other toxics, so workers are not bringing toxic materials home to their families.

Community Level Impacts

The academic researcher interviewed noted three considerations affecting the impacts on communities: facility siting, emissions from transportation, and emissions from processing.

The U.S. EPA provides guidance on how to use their EJ Screen tool when siting renewable energy facilities and other industrial facilities. Policies could be established to require use of the EJ screening tool to examine environmental justice issues related to potential locations for solar recycling facilities. When facilities are located in communities that already bear a higher burden – due to increased traffic, reduced tree cover, flooding, high asthma rates, and other environmental disparities – another facility would further compound the environmental impacts on the community.

Because truck traffic often overburdens environmental justice communities, the transportation impacts of solar recycling could also be considered. It is unclear if different policies would incentivize different transportation networks that would have different impacts. A student at San Jose University built a GIS reverse logistics model for the Bay Area that included a couple different collection center scenarios and modeling transporting waste to a site in Nevada. A similar model could be used to assess the transportation impacts of solar recycling, though it is outside the scope of the current study.

A community where a solar recycling facility is located would also want to know what the facility may be processing and burning. For example, battery recycling includes burning and would produce emissions. Lithium-ion batteries also contain PFAS, so an analysis of how PFAS emissions may affect local water resources should be considered.

Lead might also be an issue with solar PV panel recycling, as solar cells are covered in a lead metallization paste. There is a push for lead-free manufacturing, and the amount of lead is going down with each generation of solar PV panel. However, panels increasingly use double-sided sided cells, so although the amount of lead in each cell is going down, total lead in panels is increasing. The study could model each policy's potential to incentivize upstream design changes.

Upstream Design Changes

Interviewees from the environmental nonprofit, academic, and tribes all expressed an interest in seeing incentives to design solar PV panel systems that were less toxic, could be reused, and could be ideally infinitely recycled, as aluminum can be. The study could model each policy's potential for incentivizing changes in design and manufacturing and incentives for reuse.

Other Environmental Considerations

The academic researcher interviewed emphasized that doing nothing would be the least environmentally preferable approach. Although landfill operations are well managed and governed and occupational safety would unlikely be a major concern, not recycling solar PV panels and system components would result in significant loss of valuable materials and potentially in lost jobs. Solar PV panel frames are usually made of aluminum, which can be infinitely recycled and valuable. Solar PV panels also contain silver; the industry is currently using 20% of the silver used annually worldwide. The purified silicon in solar PV panels ought to be recovered and recycled, as should the batteries and inverters that are part of every solar system. A lot of mining and the detrimental impacts of mining could be avoided by recovering the aluminum, silver, silicon, and other materials that make up solar energy systems.

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